

AD-A038 612

AVCO EVERETT RESEARCH LAB INC EVERETT MASS
HIGH POWER DENSITY MHD GENERATORS. (U)
MAR 76 R KESSLER

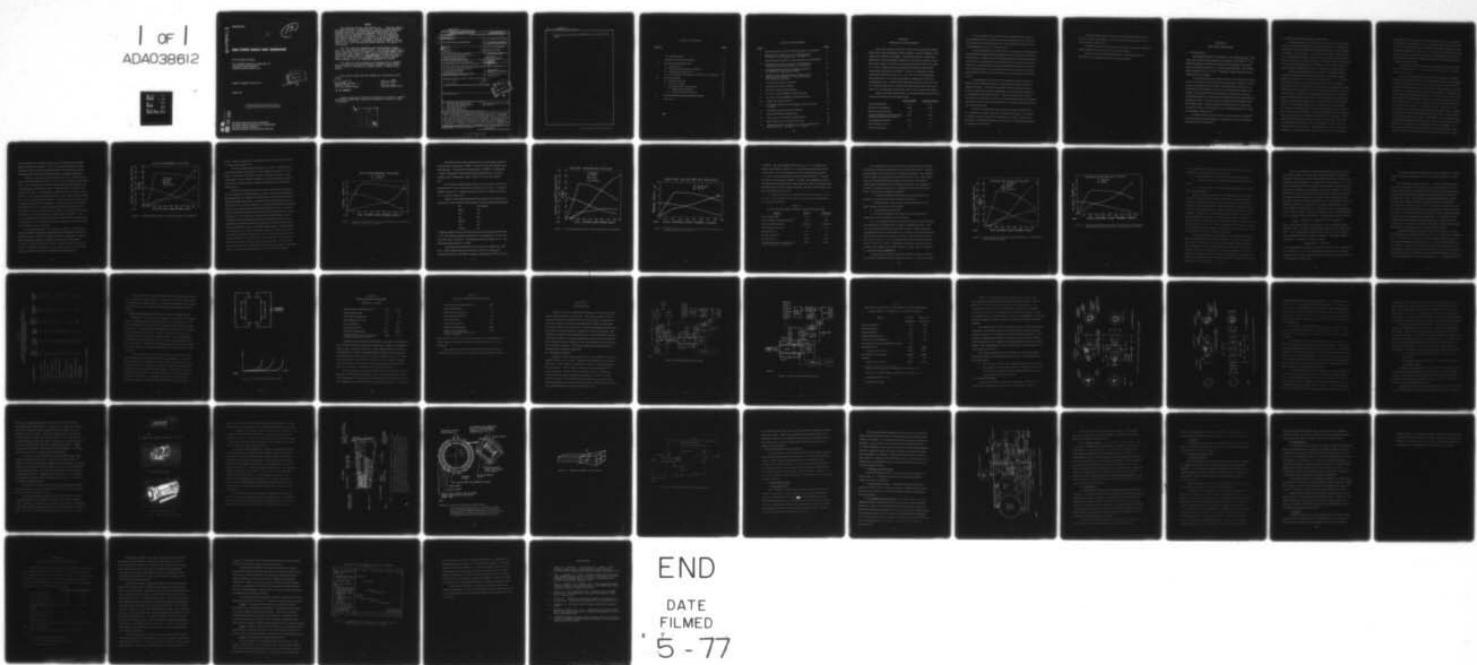
UNCLASSIFIED

F/G 10/2

F33615-75-C-2047
NL

AFAPL-TR-76-71

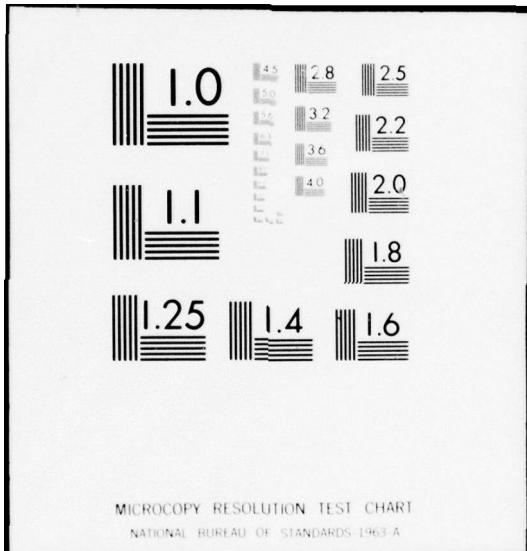
| OF |
ADA038612



END

DATE
FILED

5 - 77



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

ADA 038612

AFAPL-TR-76-71

(13)

HIGH POWER DENSITY MHD GENERATORS

FINAL TECHNICAL REPORT

AVCO EVERETT RESEARCH LABORATORY, INC.
2385 REVERE BEACH PARKWAY
EVERETT, MASSACHUSETTS 02149

TECHNICAL REPORT AFAPL-TR-76-71



MARCH 1976

Approved for public release; distribution unlimited

AU NO. _____
DDC FILE COPY

AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

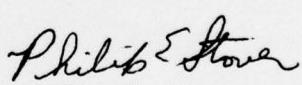
This final report was submitted by Avco Everett Research Laboratory, Inc., under Contract F33615-75-C-2047. The effort was sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio, Project No. 3145, Task No. 26 and Work Unit No. 24 with Project Engineer Robert F. Cooper/AFAPL/POP-2 as Project Engineer In-Charge. Contract Project Scientist Robert Kessler of Avco Everett Research Laboratory, Inc., was technically responsible for the work.

This report has been reviewed by the Information Office, (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.


Robert F. Cooper

High Power Program Manager


Philip E. Stover

High Power Branch Chief

FOR THE COMMANDER

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

AIR FORCE - 7 MARCH 77 - 125

A

<input type="checkbox"/>	<input type="checkbox"/>		
100	200	300	400
500	600	700	800
900	1000	1100	1200
1300	1400	1500	1600
1700	1800	1900	2000
2100	2200	2300	2400
2500	2600	2700	2800
2900	3000	3100	3200
3300	3400	3500	3600
3700	3800	3900	4000
4100	4200	4300	4400
4500	4600	4700	4800
4900	5000	5100	5200
5300	5400	5500	5600
5700	5800	5900	6000
6100	6200	6300	6400
6500	6600	6700	6800
6900	7000	7100	7200
7300	7400	7500	7600
7700	7800	7900	8000
8100	8200	8300	8400
8500	8600	8700	8800
8900	9000	9100	9200
9300	9400	9500	9600
9700	9800	9900	10000
10100	10200	10300	10400
10500	10600	10700	10800
10900	11000	11100	11200
11300	11400	11500	11600
11700	11800	11900	12000
12100	12200	12300	12400
12500	12600	12700	12800
12900	13000	13100	13200
13300	13400	13500	13600
13700	13800	13900	14000
14100	14200	14300	14400
14500	14600	14700	14800
14900	15000	15100	15200
15300	15400	15500	15600
15700	15800	15900	16000
16100	16200	16300	16400
16500	16600	16700	16800
16900	17000	17100	17200
17300	17400	17500	17600
17700	17800	17900	18000
18100	18200	18300	18400
18500	18600	18700	18800
18900	19000	19100	19200
19300	19400	19500	19600
19700	19800	19900	20000
20100	20200	20300	20400
20500	20600	20700	20800
20900	21000	21100	21200
21300	21400	21500	21600
21700	21800	21900	22000
22100	22200	22300	22400
22500	22600	22700	22800
22900	23000	23100	23200
23300	23400	23500	23600
23700	23800	23900	24000
24100	24200	24300	24400
24500	24600	24700	24800
24900	25000	25100	25200
25300	25400	25500	25600
25700	25800	25900	26000
26100	26200	26300	26400
26500	26600	26700	26800
26900	27000	27100	27200
27300	27400	27500	27600
27700	27800	27900	28000
28100	28200	28300	28400
28500	28600	28700	28800
28900	29000	29100	29200
29300	29400	29500	29600
29700	29800	29900	30000
30100	30200	30300	30400
30500	30600	30700	30800
30900	31000	31100	31200
31300	31400	31500	31600
31700	31800	31900	32000
32100	32200	32300	32400
32500	32600	32700	32800
32900	33000	33100	33200
33300	33400	33500	33600
33700	33800	33900	34000
34100	34200	34300	34400
34500	34600	34700	34800
34900	35000	35100	35200
35300	35400	35500	35600
35700	35800	35900	36000
36100	36200	36300	36400
36500	36600	36700	36800
36900	37000	37100	37200
37300	37400	37500	37600
37700	37800	37900	38000
38100	38200	38300	38400
38500	38600	38700	38800
38900	39000	39100	39200
39300	39400	39500	39600
39700	39800	39900	40000
40100	40200	40300	40400
40500	40600	40700	40800
40900	41000	41100	41200
41300	41400	41500	41600
41700	41800	41900	42000
42100	42200	42300	42400
42500	42600	42700	42800
42900	43000	43100	43200
43300	43400	43500	43600
43700	43800	43900	44000
44100	44200	44300	44400
44500	44600	44700	44800
44900	45000	45100	45200
45300	45400	45500	45600
45700	45800	45900	46000
46100	46200	46300	46400
46500	46600	46700	46800
46900	47000	47100	47200
47300	47400	47500	47600
47700	47800	47900	48000
48100	48200	48300	48400
48500	48600	48700	48800
48900	49000	49100	49200
49300	49400	49500	49600
49700	49800	49900	50000
50100	50200	50300	50400
50500	50600	50700	50800
50900	51000	51100	51200
51300	51400	51500	51600
51700	51800	51900	52000
52100	52200	52300	52400
52500	52600	52700	52800
52900	53000	53100	53200
53300	53400	53500	53600
53700	53800	53900	54000
54100	54200	54300	54400
54500	54600	54700	54800
54900	55000	55100	55200
55300	55400	55500	55600
55700	55800	55900	56000
56100	56200	56300	56400
56500	56600	56700	56800
56900	57000	57100	57200
57300	57400	57500	57600
57700	57800	57900	58000
58100	58200	58300	58400
58500	58600	58700	58800
58900	59000	59100	59200
59300	59400	59500	59600
59700	59800	59900	60000
60100	60200	60300	60400
60500	60600	60700	60800
60900	61000	61100	61200
61300	61400	61500	61600
61700	61800	61900	62000
62100	62200	62300	62400
62500	62600	62700	62800
62900	63000	63100	63200
63300	63400	63500	63600
63700	63800	63900	64000
64100	64200	64300	64400
64500	64600	64700	64800
64900	65000	65100	65200
65300	65400	65500	65600
65700	65800	65900	66000
66100	66200	66300	66400
66500	66600	66700	66800
66900	67000	67100	67200
67300	67400	67500	67600
67700	67800	67900	68000
68100	68200	68300	68400
68500	68600	68700	68800
68900	69000	69100	69200
69300	69400	69500	69600
69700	69800	69900	70000
70100	70200	70300	70400
70500	70600	70700	70800
70900	71000	71100	71200
71300	71400	71500	71600
71700	71800	71900	72000
72100	72200	72300	72400
72500	72600	72700	72800
72900	73000	73100	73200
73300	73400	73500	73600
73700	73800	73900	74000
74100	74200	74300	74400
74500	74600	74700	74800
74900	75000	75100	75200
75300	75400	75500	75600
75700	75800	75900	76000
76100	76200	76300	76400
76500	76600	76700	76800
76900	77000	77100	77200
77300	77400	77500	77600
77700	77800	77900	78000
78100	78200	78300	78400
78500	78600	78700	78800
78900	79000	79100	79200
79300	79400	79500	79600
79700	79800	79900	80000
80100	80200	80300	80400
80500	80600	80700	80800
80900	81000	81100	81200
81300	81400	81500	81600
81700	81800	81900	82000
82100	82200	82300	82400
82500	82600	82700	82800
82900	83000	83100	83200
83300	83400	83500	83600
83700	83800	83900	84000
84100	84200	84300	84400
84500	84600	84700	84800
84900	85000	85100	85200
85300	85400	85500	85600
85700	85800	85900	86000
86100	86200	86300	86400
86500	86600	86700	86800
86900	87000	87100	87200
87300	87400	87500	87600
87700	87800	87900	88000
88100	88200	88300	88400
88500	88600	88700	88800
88900	89000	89100	89200
89300	89400	89500	89600
89700	89800	89900	90000
90100	90200	90300	90400
90500	90600	90700	90800
90900	91000	91100	91200
91300	91400	91500	91600
91700	91800	91900	92000
92100	92200	92300	92400
92500	92600	92700	92800
92900	93000	93100	93200
93300	93400	93500	93600
93700	93800	93900	94000
94100	94200	94300	94400
94500	94600	94700	94800
94900	95000	95100	95200
95300	95400	95500	95600
95700	95800	95900	96000
96100	96200	96300	96400

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM										
1. REPORT NUMBER <i>(18) AFAPL-TR-76-71</i>	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER										
4. TITLE (and Subtitle) HIGH POWER DENSITY MHD GENERATORS		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report										
6. AUTHOR(s) <i>(19) Robert R. Kessler</i>		7. PERFORMING ORG. REPORT NUMBER										
8. CONTRACT OR GRANT NUMBER(s) <i>(15) F33615-75-C-2047</i>		9. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Task 314526 Work Unit 31452624										
10. PERFORMING ORGANIZATION NAME AND ADDRESS Avco Everett Research Laboratory, Inc. 2385 Revere Beach Parkway Everett, Massachusetts 02149		11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Aero Propulsion Laboratory Wright-Patterson Air Force Base, Ohio 45433										
12. REPORT DATE <i>(11) March 1976</i>		13. NUMBER OF PAGES 57										
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Air Force Aero Propulsion Laboratory Air Force Systems Command United States Air Force Wright-Patterson Air Force Base, Ohio		15. SECURITY CLASS. (of this report) Unclassified										
16. DISTRIBUTION STATEMENT (of this Report) <i>(16) Approved for public release; distribution unlimited</i>		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE <i>(17) APR 26 1977</i>										
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) <i>(18) DDCI APPROVED FOR PUBLIC RELEASE APR 26 1977</i>												
18. SUPPLEMENTARY NOTES <i>(19) C</i>												
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) <table> <tr><td>1. High Performance MHD Generator</td><td>6. Direct Energy Conversion Systems</td></tr> <tr><td>2. High Power Density MHD Generator</td><td>7. MHD Generators</td></tr> <tr><td>3. Lightweight MHD Generator</td><td></td></tr> <tr><td>4. Burst Power Supply</td><td></td></tr> <tr><td>5. Fast Start Power Systems</td><td></td></tr> </table>			1. High Performance MHD Generator	6. Direct Energy Conversion Systems	2. High Power Density MHD Generator	7. MHD Generators	3. Lightweight MHD Generator		4. Burst Power Supply		5. Fast Start Power Systems	
1. High Performance MHD Generator	6. Direct Energy Conversion Systems											
2. High Power Density MHD Generator	7. MHD Generators											
3. Lightweight MHD Generator												
4. Burst Power Supply												
5. Fast Start Power Systems												
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Operating parameters were calculated for MHD generators operating at power densities in the channel of 500 MW/m ³ and with power outputs of 30 - 35 MW (nominal). Liquid-fueled generators, using hydrocarbon fuels such as JP-4 or RP-1 and oxygen, and solid fuel generators were investigated. Designs of both liquid and solid fuel generators are described, and estimates of their weights and sizes are given. Operation of generators at power densities of 1000 MW/m ³ was investigated. Assessments of feasibility and risks involved in achieving high power density operation are made. A development plan for construction of												

*048450**4B*

void
UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

flightweight high power density MHD generator power supplies is presented.

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
List of Illustrations	ii
I INTRODUCTION AND SUMMARY	1
II OPERATING PARAMETERS	5
A. Introduction	5
B. Generator Performance Parameters	6
C. Channel Risk Assessment	16
D. Operating Characteristics of 1000 MW/m ³ Generators	23
III SYSTEM DESIGN	27
A. Estimated Weights	27
B. Generator Design	31
C. Reactant Storage and Handling	43
1. Liquid Fuel Combustor	43
2. Solid Propellant Combustor	47
IV CONCLUSIONS AND RECOMMENDATIONS	51
References	57

LIST OF ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
1 Operating Characteristics of RP/O ₂ System at 500 MW/m ³	9
2 Magnetic Field, Static Pressure, Hall Parameter Distributions of RP/O ₂ System at 500 MW/m ³	11
3 Operating Characteristics, Solid Fuel System at 500 MW/m ³	13
4 Magnetic Field, Static Pressure, Hall Parameter Distribution, Solid Fuel System at 500 MW/m ³	14
5 Operating Characteristics for Solid Fuel System at 500 MW/m ³ , Reduced Mass Flow	17
6 Magnetic Field, Static Pressure, Hall Parameter Distribution for 500 MW/m ³ Solid Fuel System, Reduced Mass Flow Rate	18
7 Frame Segmentation and Control	24
8 RP/O ₂ System Block Diagram	28
9 Solid Fuel System Block Diagram	29
10 Gas Flow Train and Magnet, RP/O ₂ System	32
11 Gas Flow Train and Magnet, Solid Fuel System	33
12 Lightweight Channel Design	37
13 Conceptual Design of the Coil Support and the Cryostat Assembly	39
14 Transverse Section through the Magnet	40
15 Multi-Cell Diffuser Configuration	41
16 Flow Diagram for Channel Cooling System	42
17 MHD Combustor Feed System Schematic	45
18 Development Plan for High Power Density (500 MW/m ³) MHD Generators. Net Power: 30 - 35 MW	54

SECTION I

INTRODUCTION AND SUMMARY

This report presents results of a study of the feasibility of portable MHD electric power generator systems operating at power densities in the channel of 500 MW/m^3 and higher. Operating parameters, weights and dimensions of MHD generators operating on various fuel-oxidizer combinations were studied, for machines with electrical power output in the range 30 - 35 MW. Design layouts were made for two systems with nominal channel power density of 500 MW/m^3 . These are a liquid fuel system operating on hydrocarbon fuels (e.g., RP-1 or JP-4) and liquid oxygen, with cesium seed, and a system operating on a double-base solid fuel, seeded with cesium. Operation of the MHD generator was considered both in a continuous mode and in a pulsed mode with a typical duty cycle of 20 pulses of 7 seconds duration per pulse, with 2 to 5 seconds between pulses.

Channel operating characteristics and system weights and dimensions for the two systems are summarized below:

	<u>RP/O₂ System</u>	<u>Solid Fuel System</u>
Power Output [MW]	31.5	33.2
System Dry Weight [kg]	2305	1695
Mass Flow Rate [kg/sec]	30	30
Total Weight (60 sec operation) [kg] (includes reactants and coolant)	4625	3820
Peak Magnetic Field [T]	4.6	3.6
Overall Diameter [m]	1.6	1.3
Overall Length [m]	3.7	3.7

The dry weight of the solid fuel system depends to some extent on the operating duration required, because the weight of the burner depends on the amount of reactant required, for a given propellant weight fraction. The propellant mass fraction assumed is 0.9.

Major development, for both systems, is required for the lightweight superconducting magnet which represents the heaviest single component of the generator. Another area of development required, for pulsed operation, is for burners, particularly of solid fueled burners capable of the required duty cycle. The potential for electrical breakdown and damage in the channels is considerably in excess of experience to date, because of the high power density operation, and development may be required in channel technology.

In comparing the two systems, the solid fuel system is about 17% lighter in total weight and requires a magnet of lower peak field than the liquid fuel system. The liquid fuel system has the advantage of using a readily available fuel-oxidizer combination, and allows pulse durations to be independent of the initial fuel load. The choice between the solid and liquid fueled generators will also be influenced by their respective operating characteristics and by the reactant storage and handling systems and auxiliary systems required.

Operation of MHD generators at power densities of 1000 MW/m^3 was considered, using the same fuels considered previously. The weight reductions achieved by this mode of operation are small, and the risk of electrical breakdown and damage to the channel is considerably higher than in operation at 500 MW/m^3 .

Section II of this report presents electrical operating characteristics of the two systems investigated, and also presents characteristics of channels operating at 1000 MW/m^3 .

Section III presents the design layout of the MHD generator, estimated system weights and some system design considerations.

Section IV contains recommendations for a development plan for construction of a prototype high power density generator.

SECTION II

OPERATING PARAMETERS

A. INTRODUCTION

Operating parameters are presented for two MHD generators, both operating at nominal power density, in the channel, of 500 MW/m^3 . One generator operates on liquid hydrocarbon fuels and oxygen, with cesium seed, and the other operates on a cesium-seeded solid fuel. The nominal power output level is 30 - 35 MW. Preliminary weight estimates are presented for the two systems.

The operating parameters shown provide some indication of the risk of failure or damage involved in the channels described. However, assessments of risk based solely on specific operating characteristics tend to underestimate the potential for serious or even destructive damage to the channel, resulting from electrical breakdown of channel wall elements. The damage potential is influenced by the channel operating characteristics, operating duration, and by the specific configuration of the channel walls and loading scheme. Detailed discussion of these factors is beyond the scope of this report, but estimates of risk and damage potential are made in paragraph C of this section.

In addition to the two systems above, which operate at 500 MW/m^3 , operating parameters and weights are presented for systems operating at power densities of 1000 MW/m^3

B. GENERATOR PERFORMANCE PARAMETERS

Typical operating characteristics of interest for the two generator systems of primary interest were calculated by means of a computer program which calculates generator operating characteristics (power output, axial fields, current density, etc.) and generator length, volume and area, etc., with channel inlet Mach number for specified input burner pressure and gas mixture (fuel, oxidizer and seed). Constraints such as Hall parameter, electrical field limitations and diffuser recovery requirements are imposed when establishing the regions of optimum operating conditions.

Operating characteristics are calculated as outlined below; the mathematical details of the analytical techniques used in the computer program are described in previous AERL publications.¹⁻⁴ It is assumed that the flow in the channel is developing rather than fully developed. Therefore, the flow is divided into an inviscid core occupying most of the channel area and a boundary layer confined to the immediate vicinity of the channel walls. Boundary layer displacement thicknesses are calculated from momentum integral equations for both electrode and insulator walls, taking into consideration shape factor, compressibility and wall-cooling effects. Wall-roughness effects on the skin friction are also included. The boundary layer shape factor is used to predict boundary layer separation or channel stall conditions. The electrical dissipation in the boundary layer is generally small compared to the wall heat transfer rate. Consequently, the usual (no MHD) compressible flow relation between velocity and enthalpy for the boundary layer is sufficiently accurate. Flow non-uniformity effects are included. Nonuniformities in velocity, electrical conductivity, and Hall parameter in the vicinity of both the electrode and

insulator walls are considered. The combustion products are assumed to be in chemical equilibrium at the local conditions and all points in the flow field, and the electron density is assumed to be in Saha equilibrium at the translation temperature of the plasma. The electrical conductivity and the Hall parameter are calculated as a function of temperature and pressure using Frost's approximation with the effects of electron attachment to OH⁻ and other species included.

The principal results from these calculations are presented in the form of graphs which show major operating characteristics of the MHD systems of interest.

The curves shown should be regarded only as typical, in that they represent operating characteristics for particular generator inlet conditions (stagnation pressure, mass flow rate, reactant mixture) and for channels designed with minimum technical risk in terms of the operating parameters presented. Tradeoffs can be made in the inlet conditions, which would result in different operating characteristics. For instance, the channel could be operated at reduced stagnation pressure, in order to reduce the convective heat transfer rate, but then a higher mass flow rate would be required for the same power output; or, the channel could be operated at a lower mass flow rate, in order to reduce the total weight of the system, including fuel, but this would result in higher axial electric fields. These tradeoffs are discussed in more detail below. Such tradeoffs are essentially between minimum total weight and minimum technical risk. The design philosophy followed was to minimize the technical risk as much as possible. Also, the generators described are not optimized, in the sense that the channel geometry, magnetic field distribution and electrical loading have not been

precisely tailored to each other to the degree necessary for the detailed design of a particular channel. The curves shown do, however, display the general features of the systems described, and neither these nor the weight estimates made will be affected greatly by further optimization.

Figures 1 and 2 present operating parameters for a generator operating on liquid hydrocarbon fuel (RP-1, JP-4, etc.) and oxygen, with cesium seed. These reactants are readily available and have been commonly used in MHD generator experiments to date. Stoichiometric combustion is assumed. The burner is regeneratively cooled by the fuel, in order to reduce heat loss. The channel is separately cooled. Power output of the generator is 31.5 MW. The generator operates at a mass flow rate of 30 kg/sec, with a stagnation pressure of 30 atmospheres. The channel inlet Mach number for this design is 2.2, at which value (approximately) the value of σu^2 is maximized, in order to maximize power density. The calculated electrical conductivity of the working fluid at the channel inlet is 49 mho/m. This value was obtained using an estimated value of 4% of the total enthalpy input for combustion losses, including combustion inefficiencies, heat losses and non-isentropic effects in the nozzle.

The operating characteristics shown are valid for a channel of two-terminal diagonal configuration operating at the design point (no axial current flow) and for a channel of segmented Faraday configuration. Figure 1 shows parameters which are indicative of the electrical and thermal "stresses" to which the channel is subject. These parameters are the electric power output IP , the transverse current density, j_y , the axial electric field E_x , and the convective heat transfer to the channel walls, q .

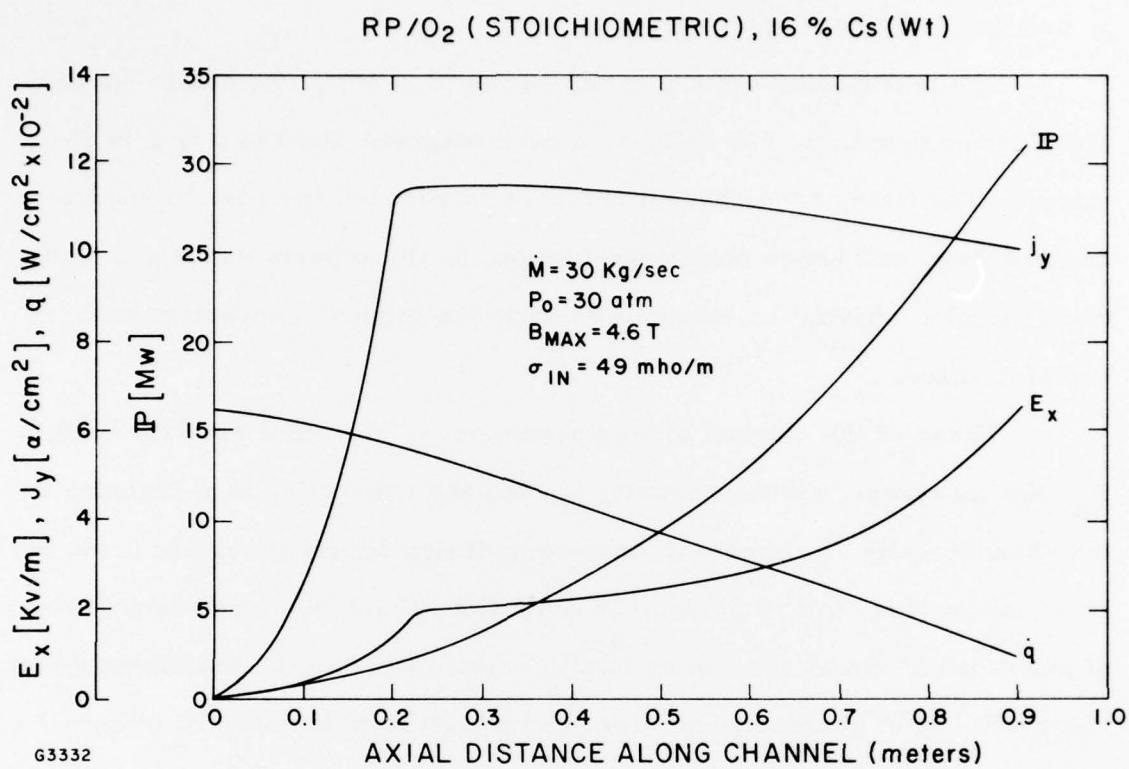


Figure 1 Operating Characteristics of RP/O₂ System at 500 MW/m³

Figure 2 shows distributions of the magnetic field, B , the static pressure, p , and the Hall parameter $\omega\tau$.

The power output of the generator is 31.5 MW. To obtain the desired power density of 500 MW/m^3 a peak magnetic field of 4.6 T is required. The field at the channel entrance is reduced in order to reduce current flow, and hence ohmic dissipation, to those parts of the gas flow train (nozzle, channel entrance) subject to the highest convective heat transfer rates.

Three of the channel stress parameters: the axial electric field, E_x , the transverse current density j_y , and the convective heat transfer to the channel walls, \dot{q} , approach or exceed design limits generally found in MHD generators built to date. The axial field reaches a maximum value of about 6.6 kV/m at the channel exit, as compared to the maximum design value of 4 kV/m generally used for generators built to date. It is noted, however, that axial fields in excess of 4 kV/m have been observed in some machines (e.g., the AERL Mk VI generator) for short times, and it is possible that fields exceeding this value by considerable margins can be sustained by generators operating for short times without need for major advances in the state-of-the-art of MHD channel design. The transverse current density j_y reaches a peak value of about 11.5 amp/cm^2 , and the convective heat transfer to the channel walls reaches a maximum value of about 650 W/cm^2 at the channel inlet. This value requires careful design of the cooling system, but presents no basic difficulties. For example, heat transfer rates up to 1 kW/cm^2 are found in conventionally cooled MHD burners, such as the compact MHD burner recently built by AERL.⁵

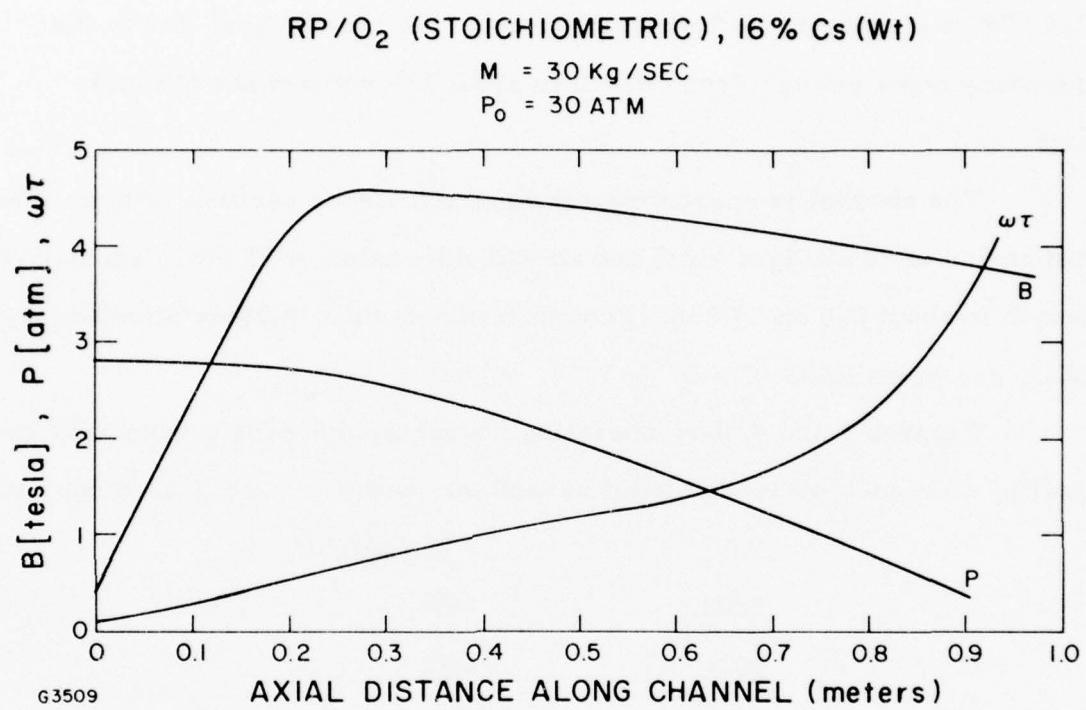


Figure 2 Magnetic Field, Static Pressure, Hall Parameter Distributions of RP/O₂ System at 500 MW/m³

The total heat loss in the channel due to convective heat transfer to the walls was calculated at 3.4 MW, or about 1% of the total thermal input to the channel. The channel wall temperature is 2000°K. An additional 2.4 MW is dissipated in the electrode wall boundary layers, due to the boundary layer voltage drop, which is about 135 volts at the channel exit.

The channel is approximately square in cross section, with an inlet dimension of 20 cm (gas side) and an exit dimension of 53 cm. The active length is about 0.9 m. Channel construction details, further dimensions, etc., are given in Section III

Figures 3 and 4 show operating characteristics for a generator operating on a cesium-seeded solid propellant, with the following composition:

Al:	23% (weight)
HMX:	8%
NC:	13%
NG:	38%
NDPA:	1%
TA:	2%
CsNO ₃ :	15%

A similar mixture has been used for generators operated previously in the U.S.⁶ The effective stagnation pressure is 30 atmospheres, and the total mass flow rate is 30 kg/sec. The channel inlet Mach number is 2.4. The generator power output is 33.2 MW.

The channel inlet conductivity in this system is higher than in the RP-1 + LOX system discussed previously, (70 mho/m compared to 49 mho/m) because of the higher stagnation temperature (4000°K compared

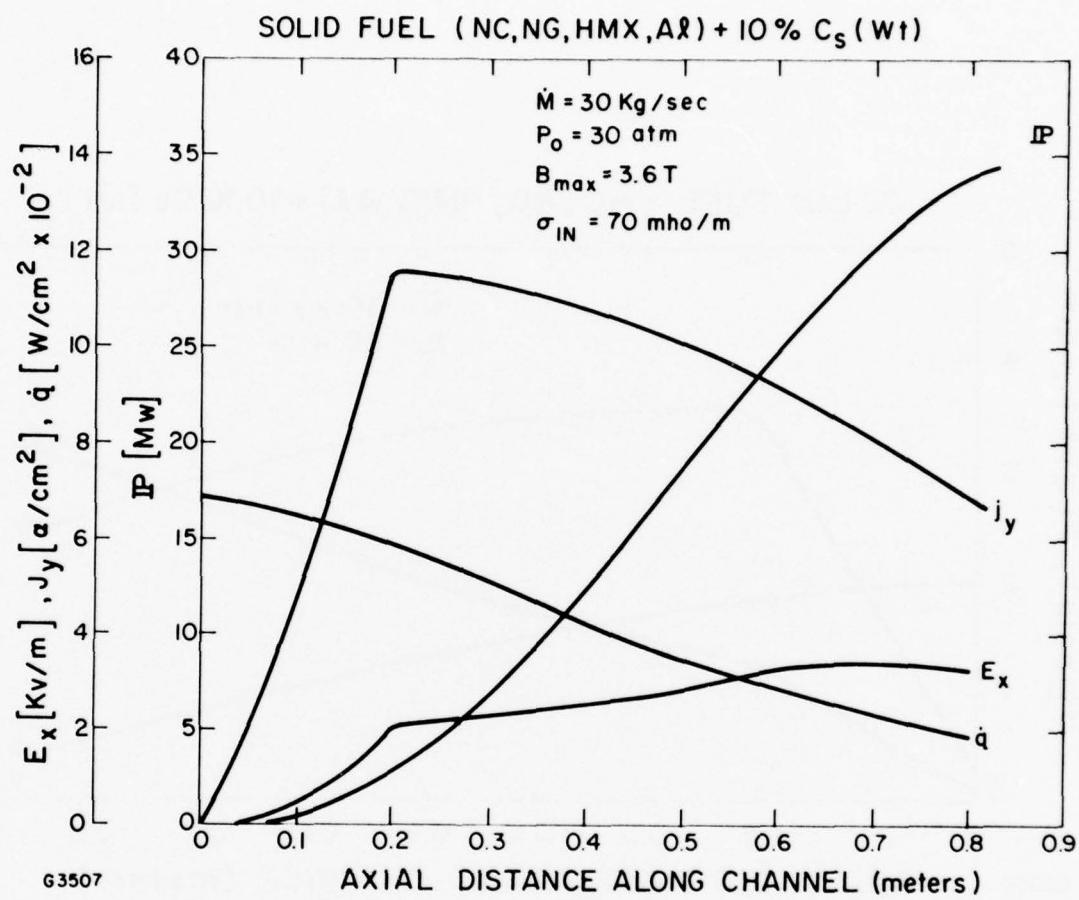


Figure 3 Operating Characteristics, Solid Fuel System at 500 MW/m^3

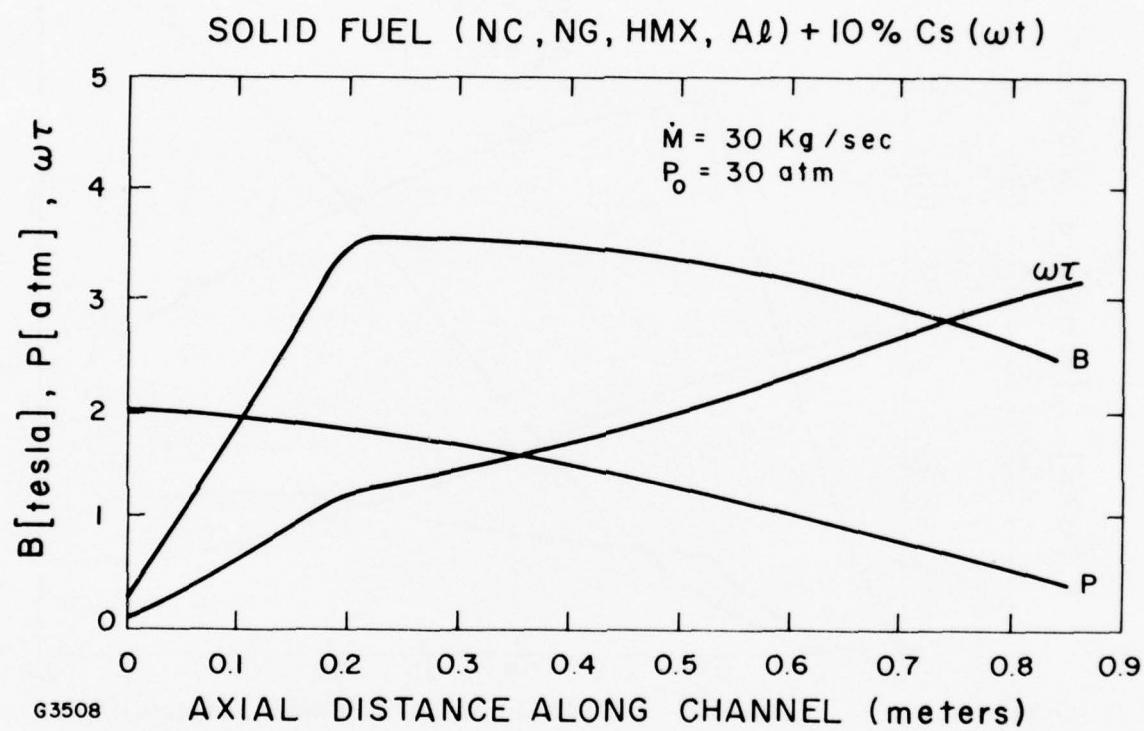


Figure 4 Magnetic Field, Static Pressure, Hall Parameter Distribution, Solid Fuel System at 500 MW/m^3

to 3500°K). The peak magnetic field required is 3.5 T, and the active length of the channel is about 0.8 m. The maximum axial electric field is about 3500 V/m, the maximum transverse current density is about 11.5 a/cm², and the maximum heat flux is about 700 W/cm². The total convective heat loss in the channel is 3.8 MW, and an additional 2 MW is dissipated due to boundary layer voltage drop (120 volts at the channel exit). The channel inlet is 24 cm square (gas side), the exit is 45 cm square, and the active length is about 0.8 m.

A comparison of the major characteristics of each system is given in Table I. The weight estimates given are for the systems described in more detail in Section III.

TABLE I
MAJOR PARAMETERS, 500 MW/m³ MHD POWER SYSTEMS

<u>System</u>	<u>RP/O₂</u>	<u>Solid Fuel</u>
Power Output [MW]	31.5	33.2
Power Density, Nominal [MW/m ³]	500	500
Mass Flow Rate [kg/sec]	30 kg/sec	30 kg/sec
Peak Magnetic Field [T]	4.6	3.6
E _x (max) [kV/m]	6.6	3.5
j _y (max) [amp/cm ²]	11.5	11.5
Dry Weight [kg]	2305	1695
Total Weight (60 sec operation) [kg] (includes reactants and coolant)	4625	3820

The stagnation pressure and mass flow rate chosen for the systems described previously are typical and can be varied within limits. Detailed tradeoff studies would be necessary to establish feasibility, risks and benefits of variations in stagnation pressure and mass flow rates. Such tradeoffs were not performed as part of this work, but some of the factors which require consideration are outlined briefly below. For example, an increase in stagnation pressure, as compared to the systems described above, could involve the following tradeoffs:

1. Increased efficiency (reduced flow rate requirement) if expansion is carried out to the same channel exit pressure.
2. Reduced diffuser requirement at the same efficiency since higher channel exit pressures are possible.
3. Increased heat transfer rate.
4. Increased magnetic field requirement (increased magnet weight) due to lower conductivity of working gas.

At a given stagnation pressure, the mass flow rate could be reduced by expanding the flow further than is required at higher flow rates. However, the channel exit pressure would then be lower, and the axial field strength higher than its already high value. Figures 5 and 6 show operating parameters for the same solid fuel as in Figs. 3 and 4 except for a mass flow rate of 25 kg/sec. It is seen that the axial field increases about 50% from 3.5 kV/m to 5.2 kV/m. Operating at even lower mass flow rates is possible, but at higher axial fields, and hence, greater risk to the channel.

C. CHANNEL RISK ASSESSMENT

The major cause of forced shutdown of MHD generators is destructive electrical breakdown between axial wall elements. Assessment of the

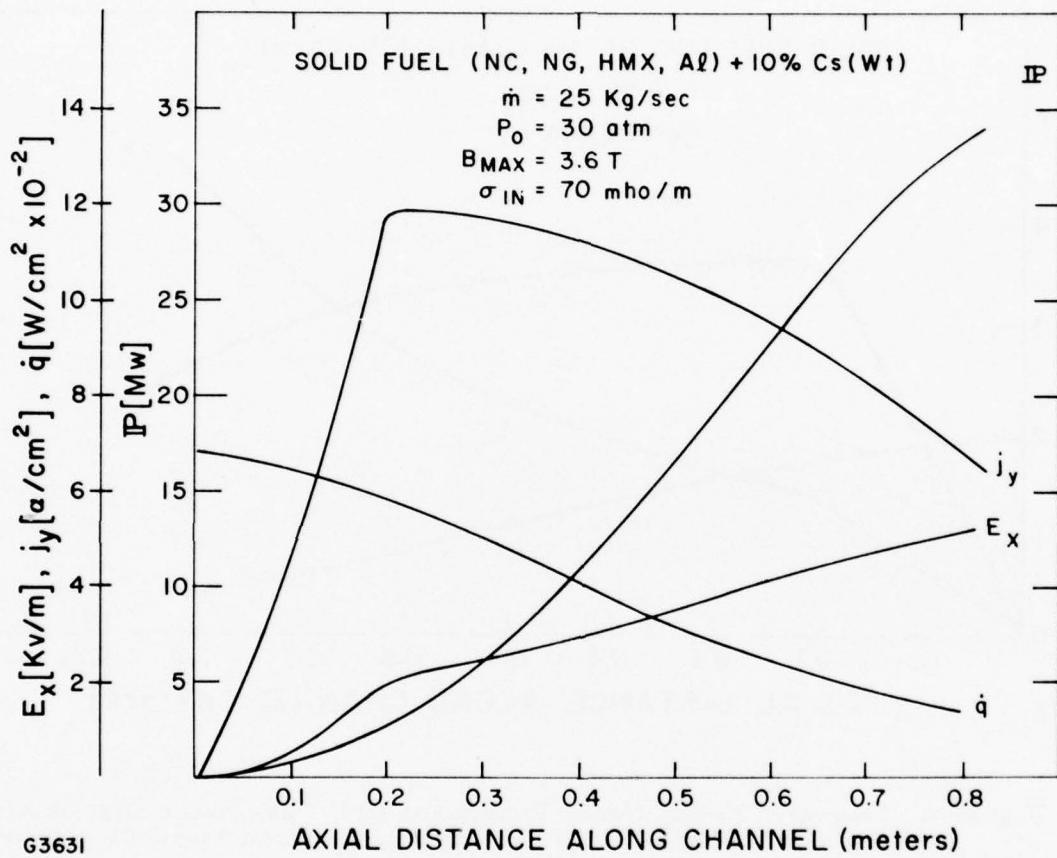


Figure 5 Operating Characteristics for Solid Fuel System at 500 MW/m^3 , Reduced Mass Flow Rate

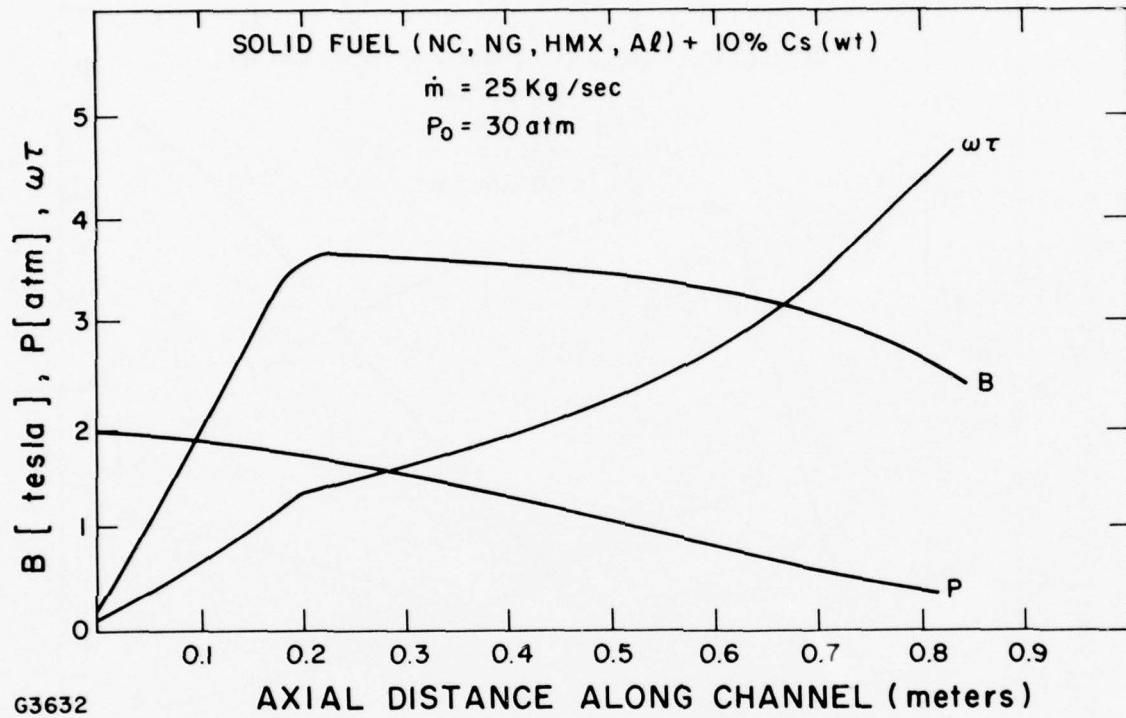


Figure 6 Magnetic Field, Static Pressure, Hall Parameter Distribution for 500 MW/m^3 Solid Fuel System, Reduced Mass Flow Rate

risk of such shutdowns, which can be associated with extensive damage to the channel, is influenced by three main factors:

- a) The probability of occurrence of axial breakdown (arcing).
- b) The potential power available either to couple into such breakdowns.
- c) The time duration over which the potential fault power can act (total operating duration).

The main criterion used to assess the probability of occurrence of breakdown is the axial electric field in the channel, because breakdown occurs in a short time, of the order of a few seconds, at values of axial field above some threshold value. High axial fields for durations exceeding a few seconds are therefore a major risk factor in channel design and operation. Operation at low axial fields does not, however, ensure that axial breakdown will not occur. Such breakdown could, for example, be initiated by the partial shorting of an interframe insulator, which could occur for a variety of reasons, e.g., local overheating of the insulator or seed or water penetration into the insulator material over some time period or over some number of generator startups or shutdowns.

Because of the fault, current leakage occurs through the insulator, with an associated amount of power dissipation. If the power dissipation in the insulator is nonuniform, as is likely, that region in which the highest power dissipation occurs reaches higher temperature than surrounding regions, with a corresponding drop in electrical resistance. This in turn draws more leakage current to that region, thus further increasing the dissipation and worsening the fault, and the net result is a strong local current concentration in the insulator, i.e., an arc.

The power available to couple into breakdowns caused by excessive axial electric fields or by faults such as described above is influenced strongly by the specific details of the channel design and its control devices. Therefore, this fault power is not shown on the curves of Figs. 1 - 6. Accurate quantitative prediction of damage power leading to channel failure is in fact not yet possible, but estimates can be made, as follows. The power which can be coupled into an insulator breakdown or fault is of the order of the voltage difference between the adjoining current-carrying elements times the current carried by such elements. For a channel of two-terminal diagonal configuration, constructed of so-called "window frames" with active length ℓ , and with pitch p , the interframe voltage is $(E_x p)$ and the frame current is $(J_y \ell_p)$, where E_x is the axial electric field in the channel and J_y the transverse current density. The fault power is then given by:

$$P_{\text{fault}} = (E_x J_y) \ell p^2 \approx (E_y J_y) \ell p^2 (\sim 45^\circ \text{ connection})$$

$(E_y J_y)$ is the power density in the generator. It is clear that the pitch should be made as small as is practically possible in order to reduce fault power. For a window frame channel, this is about 1 cm, since window frames thinner than this are difficult to fabricate. The power density is 500 MW/m³. Assuming 1 cm pitch, we have:

$$P_{\text{fault}} [\text{watts}] = 500 \ell (\text{cm})$$

The RP/O₂ channel has an inlet cross section of 20 cm x 20 cm and an exit cross section 53 cm x 53 cm as described previously. Thus, a typical dimension ℓ for a frame about in the middle of the channel is 36.5 cm and the fault power is about 18 kW.

The solid fuel channel has dimensions of 24 cm (inlet) and 45 (outlet) with an average frame dimension of 34.5 cm, and the fault power is about 17 kW.

The channel risk factors listed in a) - c) above, together with other performance parameters of interest for various generators are shown in Table II, which lists as a summary of the present status of this technology, combustion-driven generators designed for high performance which have been operated to date. Both liquid and solid-fueled generators are listed. The Mk V (two terminal) and Pamir-1 generators have non-segmented electrode walls without insulators. These have a different breakdown mechanism from the other channels shown, and so comparison on the same basis is not valid. The 30 MW generator in the table is a two-terminal diagonally connected channel of window frame construction. It is seen that in terms of fault power and operating duration, the high power density generators considered herein operate in a regime considerably in excess of the existing state-of-the-art and thus must be considered high risk devices.

A potential technique by which the risk can be reduced is to reduce the breakdown power available to produce an arc or to couple into an insulator fault. For a fixed value of pitch it was shown that the breakdown power increases linearly with the generator size, i.e., scales up like the power per unit wall area. When the generator size becomes large enough, as in the design channel, so that excessive breakdown power exists, the breakdown power per wall element can be kept below the value which would result in wall destruction by limiting the size of the wall element, i.e., by splitting the frames.

TABLE II

TYPICAL OPERATING PARAMETERS OF VARIOUS
COMBUSTION DRIVEN MHD GENERATORS COMPARED TO
DESIGN 30 MW MHD GENERATOR

MHD GENERATOR	Mass Flow Rate (kg/sec)	Power Density (MW/m ³)	Power Output (MW)	Axial Electric Field (kV/m)	Operating Duration (sec)	Breakdown Power (kW)
1. MK II - Faraday	2.7	40	1.5	1.5	10	3.2
2. MK II - Circular Hall	4.3	20	1.0	2.3	10	0.5
3. LORHO - Pilot	52	10	18	2.8	60	1.5
4. MK V - Segmented	52	10	32	1.5	60	5
5. MK V - Two Terminal	50	16	25	•0%*	60	-
6. APL High Performance	0.82	150	0.4	2.7	10	0.75
7. VIKING I	2.7	75	1.4	2	3	1
8. Hercules (Solid Fuel)	3.3	120	2.4	4	5	2.2
9. Pamir I - USSR (Solid Fuel)	25	500	15	0%	3	-
10. 30 MW Design (RP/O ₂)	30	500	30	6.6	60	18
11. 30 MW Design (Solid Fuel)	30	500	30	3.5	60	17

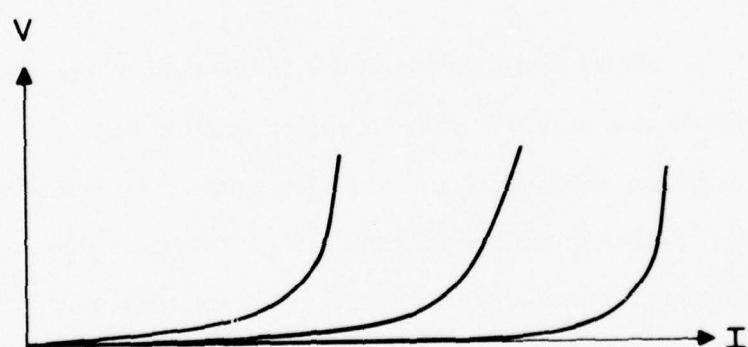
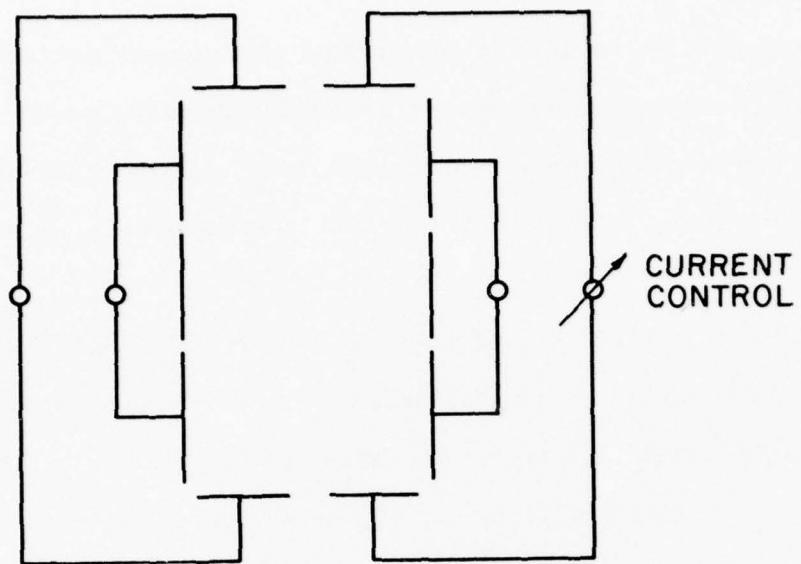
* Two terminal Faraday Configuration

This technique can be used in conjunction with current control devices (e.g., resistors, in the simplest case) in order to reduce the power capable of coupling into any single element. A possible segmentation/control scheme, typical of that used in the AERL Mk VI long-duration generator, is shown in Fig. 7.

D. OPERATING CHARACTERISTICS OF 1000 MW/m^3 GENERATORS

Operation of channels at power densities of 1000 MW/m^3 was investigated. In principle, these high power densities can be obtained by use of increased magnetic fields, and/or by use of gases with higher value of the product σu^2 . For the reactants investigated, the product σu^2 was approximately maximized, and for these reactants, high power densities can be achieved only by use of increased magnetic fields. This results in large increases in axial electric field and thus increases the risk of axial breakdown in the channel. Furthermore, the high magnetic fields required result in heavier magnets, which offsets the weight savings which otherwise might be expected.

Table III shows some parameters of the cesium-seeded solid fuel system operated at a nominal power density of 1000 MW/m^3 . Characteristics for operation at 500 MW/m^3 are also shown for comparison. It can be seen that at power densities of 1000 MW/m^3 axial fields in the channel are high, and that the reduction in total weight is less than 10% compared to operation at 500 MW/m^3 . The axial fields can be reduced by operation at higher mass flow rate, as explained previously, but the total weight, including reactants, is then greater for operating durations of interest.



G2738

Figure 7 Frame Segmentation and Control

TABLE III
SYSTEM WEIGHTS COMPARISON
(Solid Fuel, Cs Seed)

Nominal Power Density [MW/m ³]	500	1000
Power Output [MW]	33	32
Mass Flow Rate [kg/sec]	30	30
Peak Magnetic Field [T]	3.6	4.5
E _x (max) [kV/m]	3.5	8.8
j _y (max) [amp/cm ²]	11.5	13.6
System Dry Weight [kg]	1695	1480
Total Weight (60 sec operation) [kg] (includes reactants and coolant)	3820	3530

Operation at power density of 1000 MW/m³ and with lower axial fields can be achieved by use of working gases with higher electrical conductivity, such as C₂N₂ + O₂ with cesium seed. This working gas has an electrical conductivity of 150 mho/m, about double that obtainable with the solid fuel. Operating parameters for this case are shown in Table IV and it is seen that axial fields reach a maximum value of about 6.5 kV/m, which is considerably less than those of the solid fuel systems operated at the same power density. Transverse current density is increased by about 15%.

The most attractive systems are the cesium seeded solid fuel systems, operated at 500 MW/m³ and the RP/O₂ system, also at 500 MW/m³. Operation at higher power density increases significantly the risks involved in channel development, with reduction in total weight of only about 10%. To choose

TABLE IV
 $\text{C}_2\text{N}_2 + \text{O}_2$ SYSTEM CHARACTERISTICS

Nominal Power Density [MW/m ³]	1000
Power Output [MW]	33.6
Mass Flow Rate [kg/sec]	30
Peak Magnetic Field [T]	4.2
E_x (max) [kV/m]	6.5
j_y (max) [amp/cm ²]	19.2
System Dry Weight [kg]	1660
System Total Weight [kg] (includes reactants and coolant for 60 sec operation)	3730

between the two systems requires consideration of reactant handling and storage systems and auxiliary systems. Some discussion is given in Section III.

The cyanogen fuel systems can probably be eliminated from consideration because the fuel is toxic and poses severe handling problems.

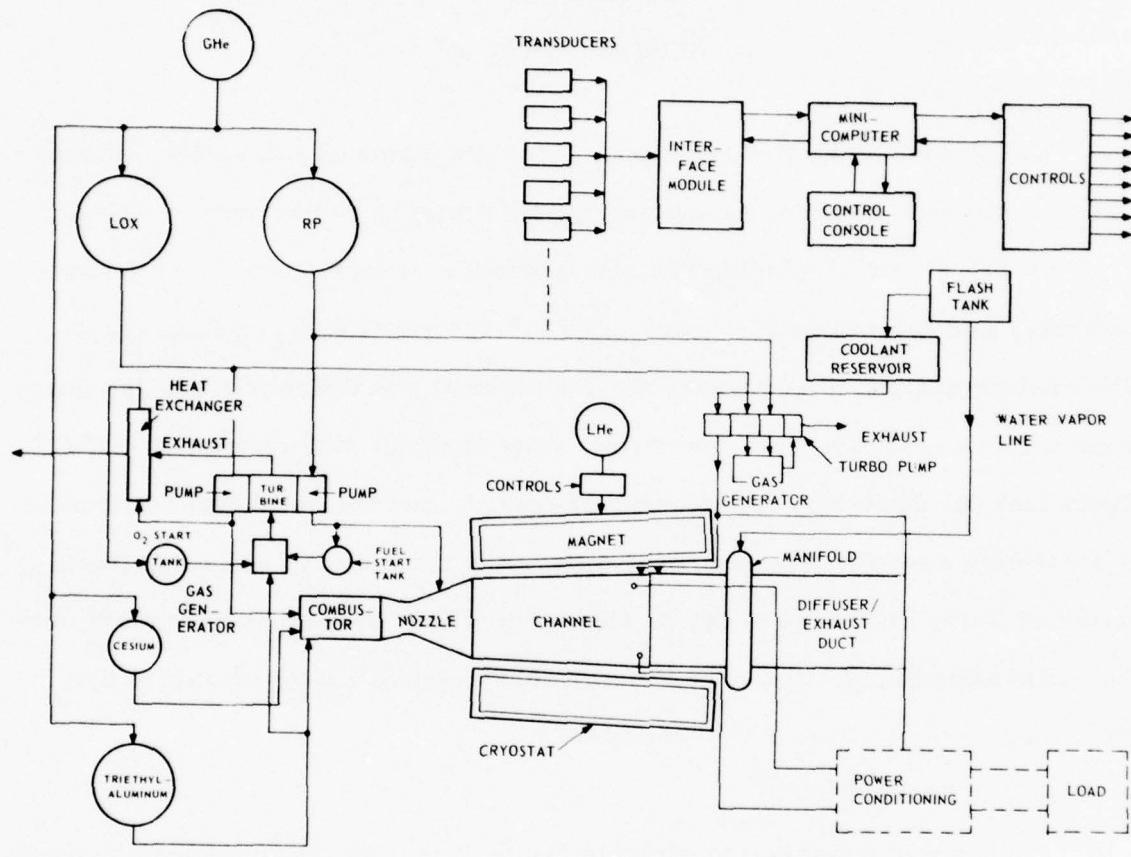
SECTION III

SYSTEM DESIGN

Figures 8 and 9 are functional block diagrams of the RP/O₂ system and the solid fuel system, respectively. The major components and subsystems are shown, including the gas flow train, magnet, cooling system controls, and the reactant storage and feed system (RP/O₂ system only). The cooling system is necessary for the channel and diffuser for pulse durations which exceed the component capability for heat sink operation. The liquid fuel combustor is regeneratively cooled, and the solid fuel combustor is ablatively cooled. The principal difference between the solid and liquid-fueled systems is that no reactant storage and feed system is necessary for the solid-fueled generator. The major subsystems of the generators are discussed in the following subsections.

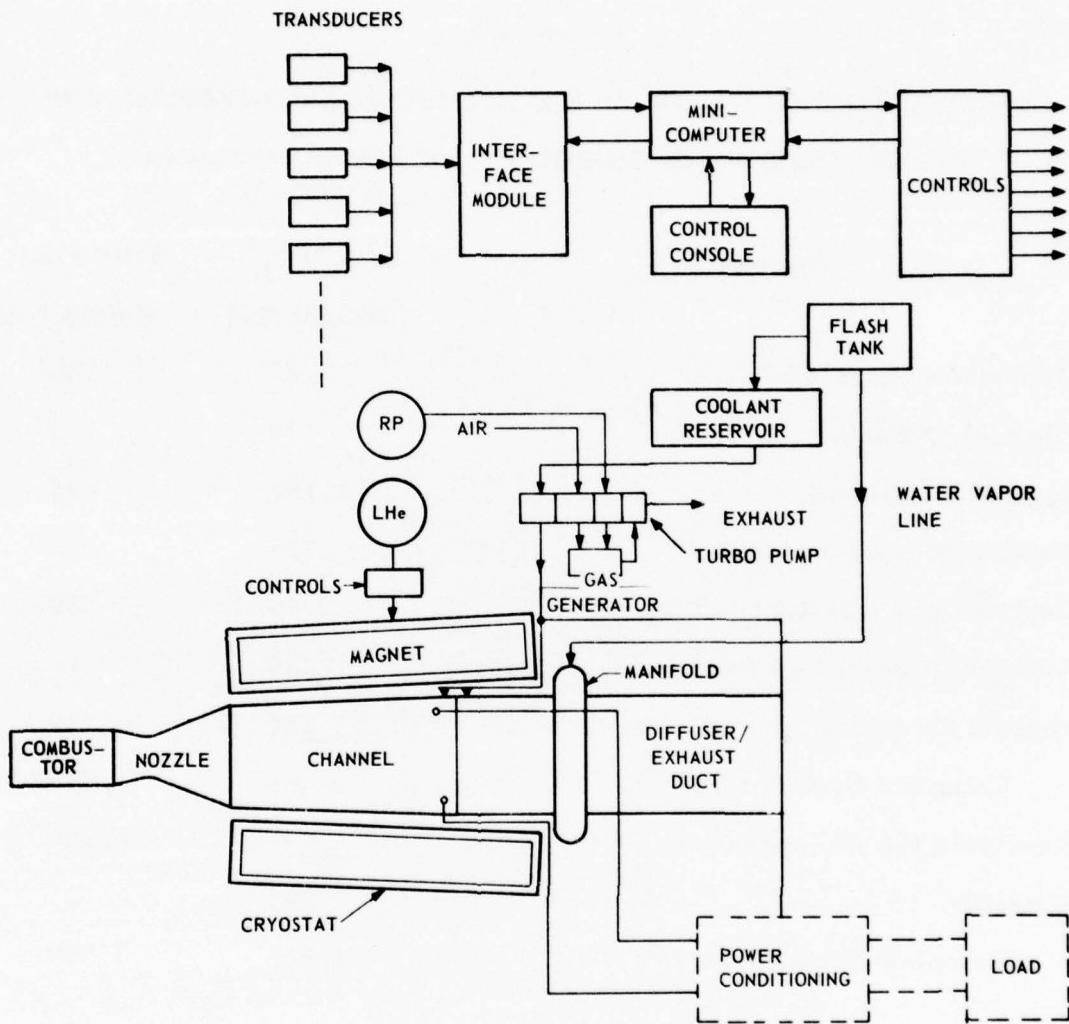
A. ESTIMATED WEIGHTS

Estimated weights are given in Table V for the MHD generator power supplies shown in Figs. 8 and 9. Weights given include those of the burner and nozzle, channel, diffuser (operation at sea level is assumed), magnet and consumables. Table V shows weights of systems designed for continuous operation, or pulsed operation at short intervals, and therefore include also the weight of a channel cooling system. In the case of the solid fuel systems, the weight of the burner depends on the total amount of reactant required, since burner and reactants are integral with each other. The propellant weight fraction was assumed to be 90%.



G2861-1

Figure 8 RP/O₂ System Block Diagram



G 2861-2

Figure 9 Solid Fuel System Block Diagram

TABLE V
ESTIMATED WEIGHTS OF 30 MW (NOMINAL) MHD GENERATORS
POWER DENSITY IN CHANNEL: 500 MW/m^3 (NOMINAL)

System	RP/O ₂ [*]	Solid Fuel ^{**}
	Weight (kg)	Weight (kg)
Combustor/Nozzle	125	180 [†]
Channel/Diffuser	130	110
Magnet Subsystem	1,190	890
Cooling Subsystem (dry)	215	215
Controls and Instrumentation	80	80
Reactant Storage and Feed Subsystem (dry)	285	-
Support Structure	<u>280</u>	<u>220</u>
Complete System (dry)	2,305	1,695
Reactants (60 sec operation)	<u>1,995</u> ^{††}	<u>1,800</u>
Coolants	325	325
Complete System (wet)	4,625	3,820

* Refers to RP/O₂ system, performance as in Figs. 1, 2.

** Refers to solid fuel system, performance as in Figs. 3, 4.

† Propellant fraction = 0.9.

†† Includes 10% ullage.

Estimates of component weights in Table V are based on recent work including the detailed design of a ground-based prototype 10 MW MHD generator,⁽⁷⁾ and represent current state-of-the-art technology. The weights shown do not include the weight of power conditioning equipment which may be required. If shielding is necessary for the magnet, the magnet weight and thus the system weight, is increased considerably. The specific amount by which the weight is increased depends on the degree of shielding required.

The cooling system in the table is primarily for cooling of the channel and diffuser, but not of the burner, since liquid fuel burners can be regeneratively cooled by the reactants and solid fuel burners are uncooled. For operation at durations up to about 30 seconds, heat-sink operation of flow train components may be possible, thus eliminating the need for the cooling system. The weight saving so made is considerable, for most systems, as can be seen from Table V.

The solid fuel system is about 17% lighter in total weight than the liquid fueled system, for 60 seconds operating time. This is possible for two main reasons:

1. The solid fuel system needs no reactant storage and feed system.
2. The magnet is of lower field, and hence, lighter weight, because of the increased conductivity of the solid fuel (70 mho/m) compared to the liquid fuel (49 mho/m).

B. GENERATOR DESIGN

Design layouts of the gas flow train and magnet for both the solid fueled and the liquid fueled generators are shown in Figs. 10 and 11.

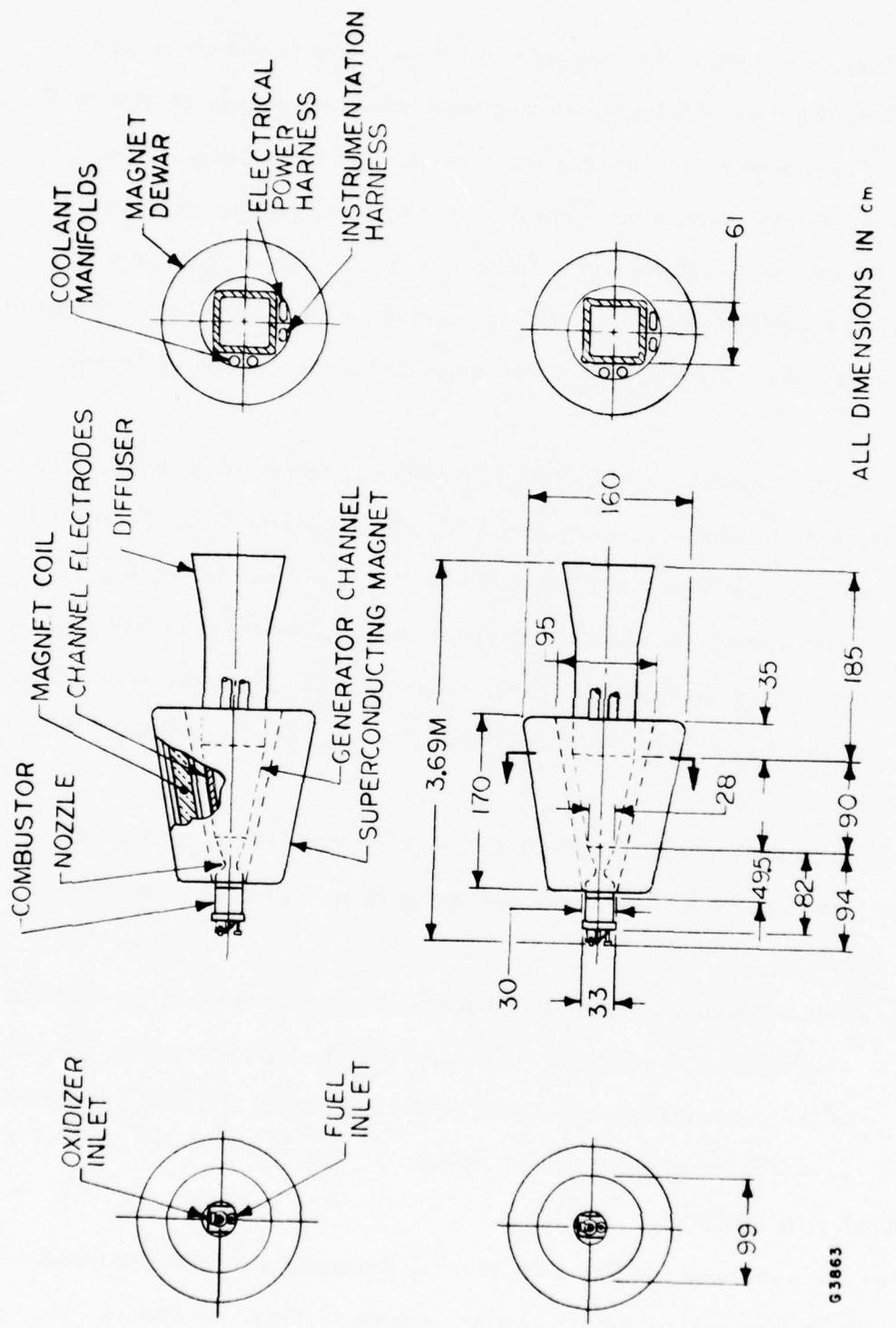


Figure 10 Gas Flow Train and Magnet, RP/O₂ System

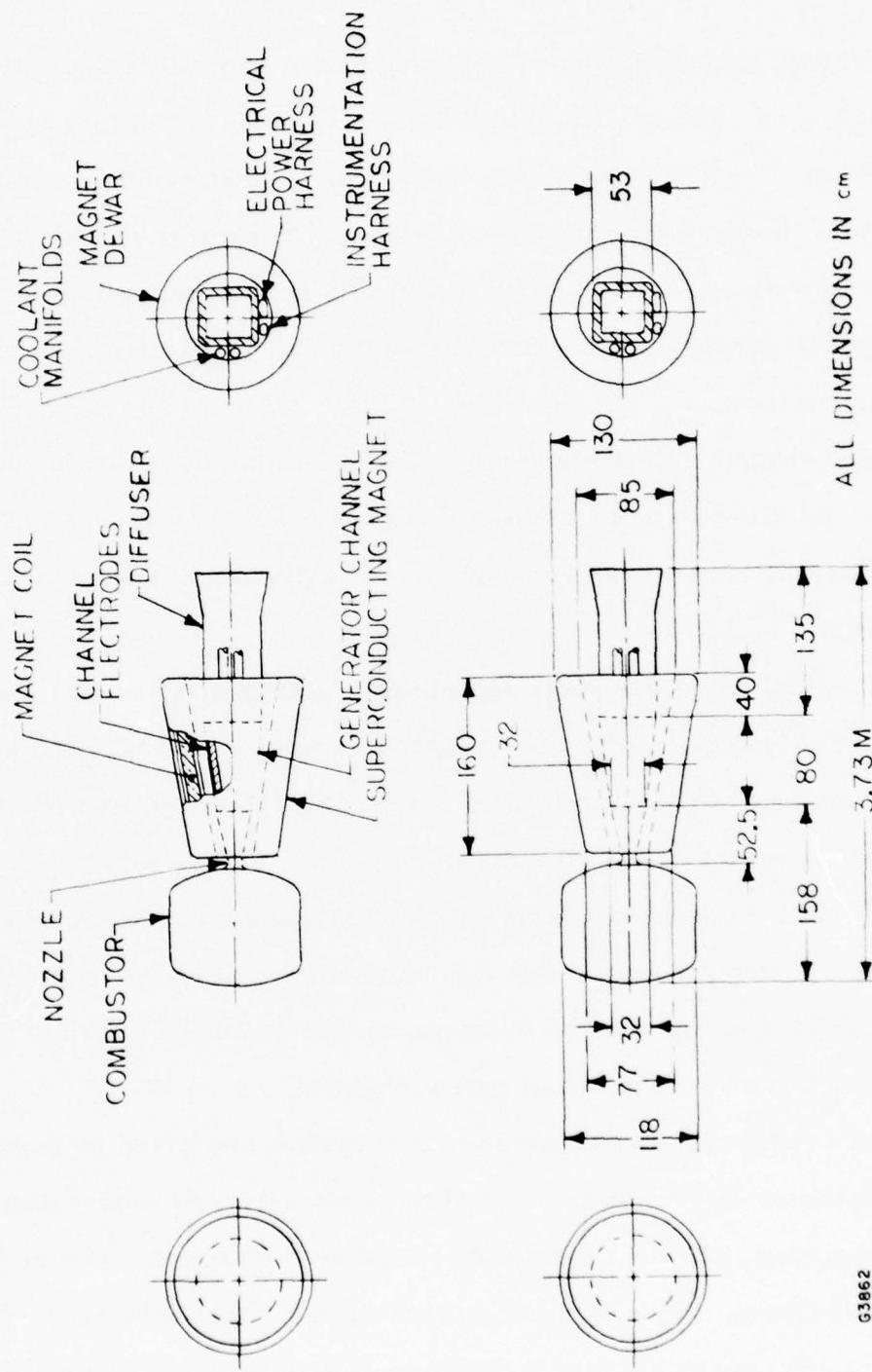


Figure 11 Gas Flow Train and Magnet, Solid Fuel System

The liquid fuel system has an overall length of 3.7 m, and an overall diameter of 1.6 m. The solid fuel system is also about 3.7 m long by 1.3 m in diameter. The solid fuel system has a shorter diffuser than the liquid fuel system, because the channel exit pressure is higher, and the diffuser can have lower pressure recovery. The solid fuel burner is larger than the liquid fuel burner, because it contains the fuel required for the total operating duration.

The channel, magnet and diffuser are similar in design for both systems, but differ to some degree in dimensions and weights. The principal difference between the two systems is in the burners and associated subsystems.

The liquid fuel burner is regeneratively cooled by the fuel, and follows conventional rocket engine practice in most respects. The need for adequate seeding of the generator means that the burner will be somewhat larger than a rocket engine with the same mass flow rate to allow adequate residence time for seed vaporization. For pulsed operation some development would be required since this type of operation imposes requirements on the ignition system, the fuel feed system and the cooling system which differ from those of conventional rocket engines.

The reactants used in the solid fuel system are based on those used for the Hercules X-259-A6 rocket motor: a nitroglycerin-nitrocellulose base, containing HMX aluminum and cesium seed material. The grain is internally burning, with a burning rate of about 0.3 inches/second. This combination is chosen because it has been used as an MHD generator fuel by Hercules Powder Company,⁽⁶⁾ at effective stagnation pressures of about

30 atmospheres, as required in the generators investigated here. For continuous operation a scaled version of the X-259-A6 motor itself could be used. The motor contains about 1200 kg of propellant and has an action time of about 33 seconds. For continuous operation of an MHD generator at 20 kg/sec for 60 seconds (nominal conditions), the web of the grain would be about twice as thick as in the rocket motor, and the grain would be shorter.

For pulsed operation of solid fueled gas generators of the size required for the MHD generator more extensive development will probably be required. Solid rocket motors operated in multiple bursts to date have been relatively small. A multiple burn solid propellant rocket motor design was used in the SRAM program. The multiple burns were accomplished by means of insulator/igniter units in the form of wafers which separate individual grains. However, the gas generator for the MHD applications would differ in the following major respects from the SRAM rocket motor:

1. A multi-burn capability of 20 is required, versus 2 for the SRAM motor.
2. The MHD gas generator is about 2 - 2 1/2 times the diameter of the SRAM motor.

In addition to the SRAM motor, which was less than half the diameter of the proposed MHD gas generator, another motor, also with separator wafers, was operated for some 40 pulses of 5 second duration per pulse.⁽⁸⁾ However, this motor has a mass flow of about 2.7 kg/sec, or about 10% that of the proposed MHD gas generator.

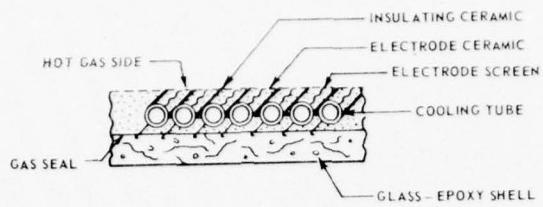
Pulsed operation using wafer insulator/igniters, in the sizes required for the MHD application, would require an end-burning grain configuration

with a faster burning rate than the grain used in the X-259-A6 motor. For typical pulsed applications, i.e., pulses of 7 seconds each at a mass flow rate of 30 kg/sec, the grain length per pulse is about 5 cm, at the burning rate of 0.3 inch/sec. The grain weight required is 210 kg, and the grain diameter can then be found to be about 1.7 m. A grain of this configuration may be difficult to ignite with SRAM-type wafers, because of the very small thickness of the grain, relative to the diameter. Higher burning rates would allow longer grains of smaller diameter. A burning rate of 0.6 inch/sec was assumed for the design layouts.

The channel, magnet, diffuser and channel cooling system follow designs developed previously for a compact 10 MW MHD generator.⁽⁷⁾ Figure 12 shows details of channel construction and also shows a non-power producing model channel which was built and tested in a previous program to verify the design ideas. The channel is constructed of essentially continuous window frames. If segmented frames are found to be necessary, as discussed in the previous section, design modifications can be made to accommodate this requirement.

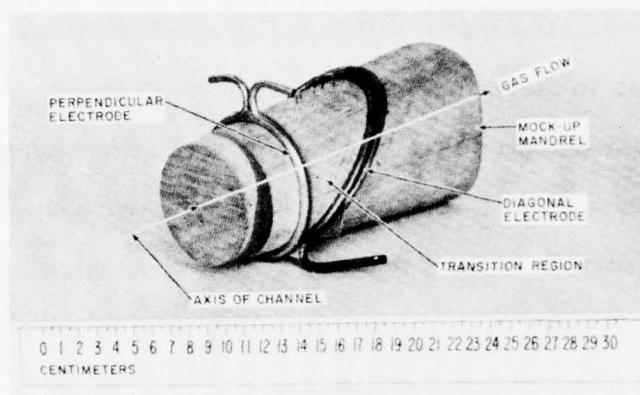
The frames are formed of thin-wall copper tubing which is shaped to form the proper cross section and which are oriented at the appropriate diagonal angle to the flow (Fig. 12(b)).

The gas side (current-carrying) surfaces are of zirconia ceramic cast between fins which are brazed to the tubes (Fig. 12(a)). Insulating ceramic (magnesia or alumina) is cast between adjacent tubes. A filament-wound glass reinforced epoxy shell is laid up around the tubes and bonded to them. The shell is the main structural member of the channel. The gas



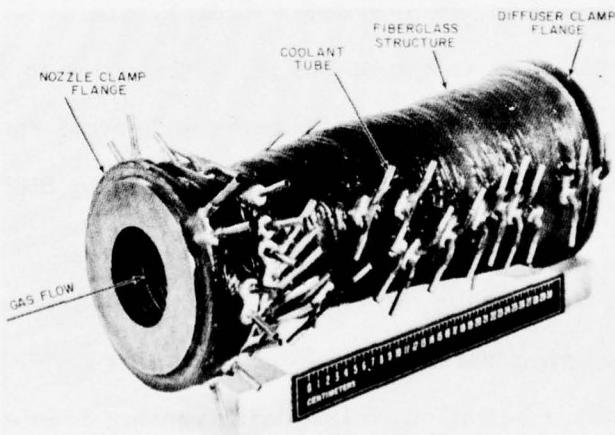
D6670

a) Lightweight Channel Construction Technique



D8619

b) Frame Construction



E1443

LIGHTWEIGHT OPERATIONAL MODEL CHANNEL WEIGHT ~50LBS

c) Lightweight Model Channel

Figure 12 Lightweight Channel Design

seal is a layer of silicon rubber between the shell and the tubes. The gas-tight seals are made around the tubes which project through the outer shell.

A conceptual design of the magnet is shown in Figs. 13 and 14. The magnet uses fully bonded coil windings to support transverse shear and compressive forces. A support structure external to the windings supports overall magnet loads elastically within deflection limits that do not induce excessive stresses in the winding structure.

The diffuser design consists of a constant area supersonic diffuser section followed by a diverging subsonic diffusion section. The length of the diffuser is governed by the pressure recovery required (ratio of ambient pressure to channel exit pressure). For recovery to 1 atmosphere (sea level) from a channel exit pressure of 0.45 atmospheres, as for the RP/O₂ system (Fig. 2), a diffuser of length equal to about 3 inlet diameters (channel exit diameter) is required. For the solid fuel case with higher channel exit pressure (Fig. 4), a shorter diffuser can be used. The diffuser can be partitioned as shown in Fig. 15 in order to reduce the effective length, but this introduces additional mechanical and cooling system complexity. Thrust loading could be minimized by bifurcation of the exhaust duct.

The cooling system for the channel is a pump-driven forced convection closed loop using water as the heat transport fluid, in combination with a secondary water boiloff open loop with venting overboard. The flow diagram for the system is shown in Fig. 16. Similar systems, but on

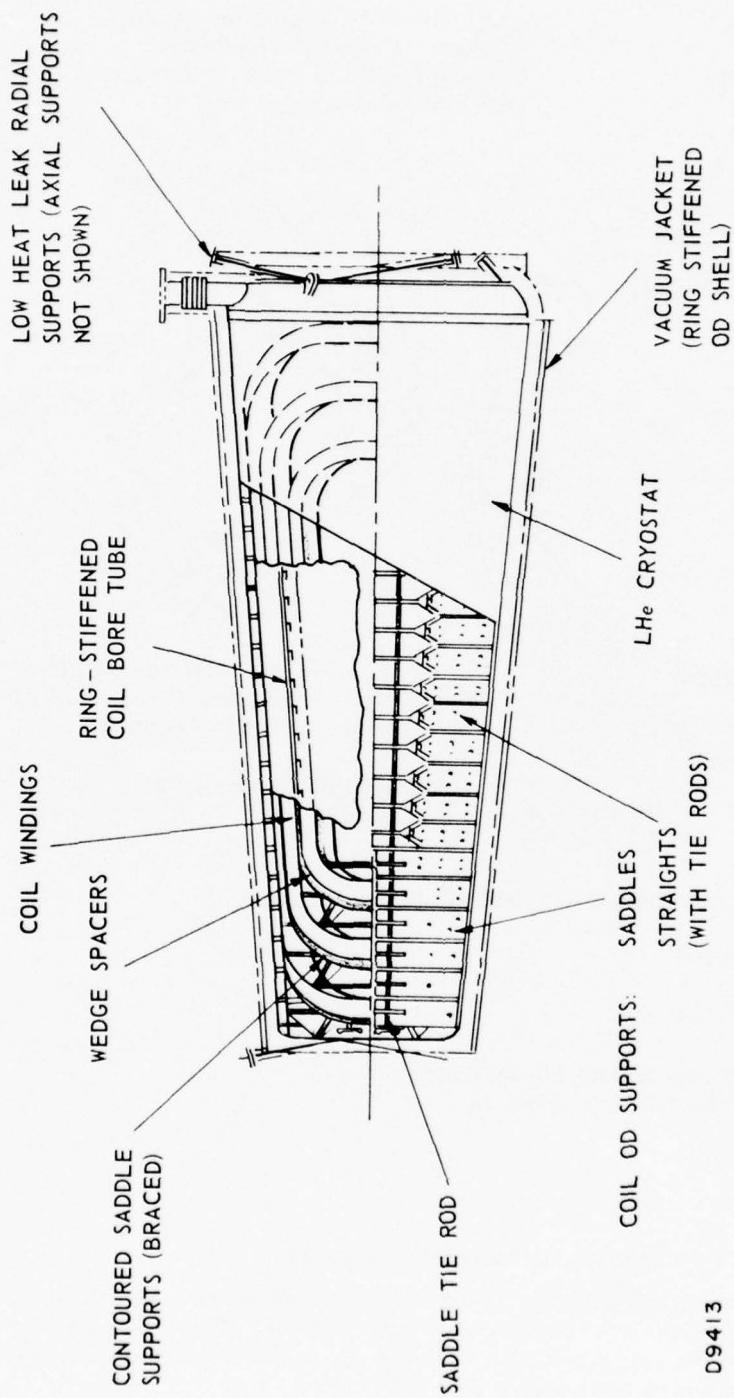
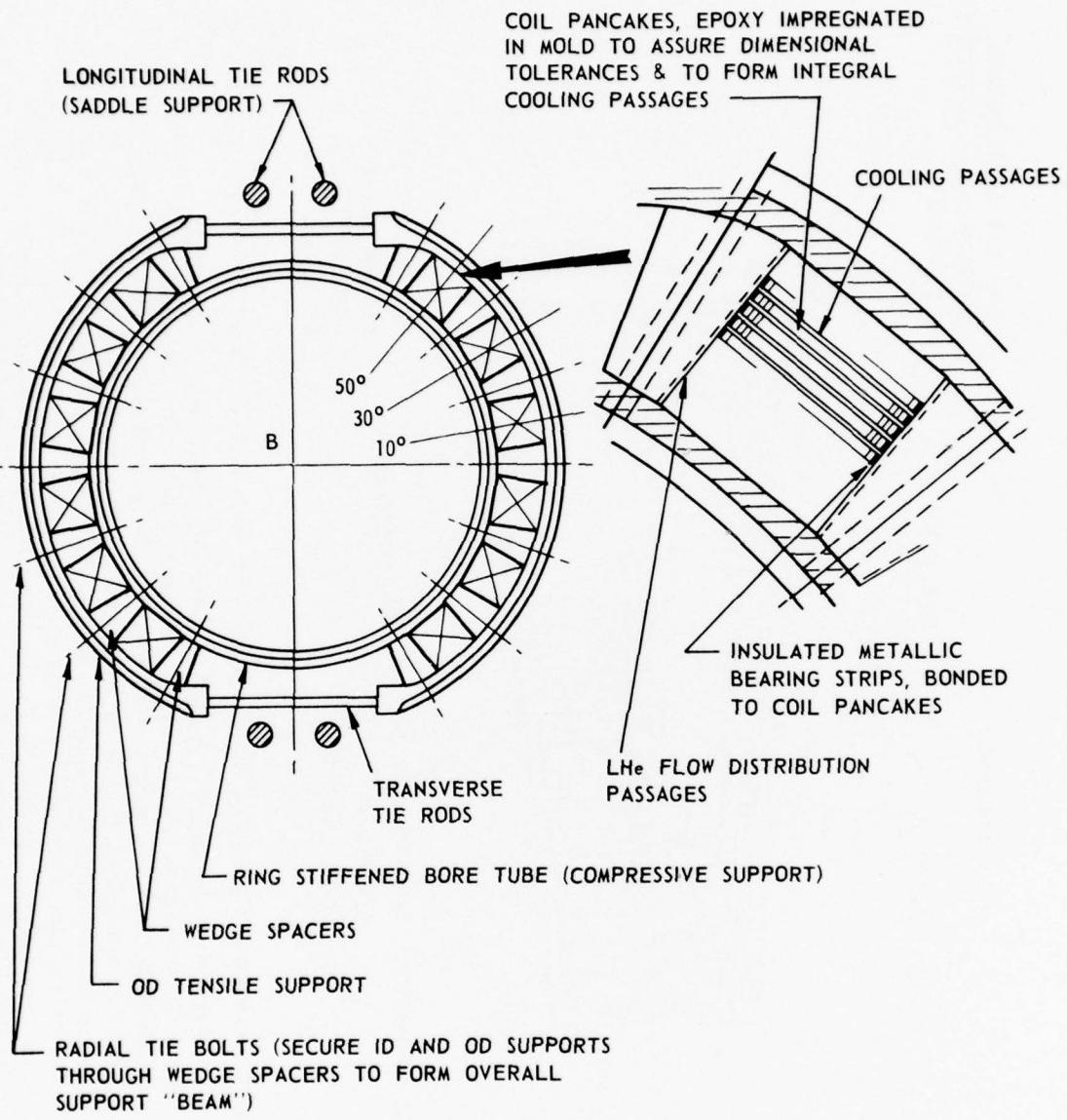


Figure 13 Conceptual Design of the Coil Support and the Cryostat Assembly
 The main features of the coil geometry, the support approach and the cryostat construction are indicated. The coil has six individual winding regions (Case No. 19 geometry). The lateral support combines the bore tube and the OD support members along with the wedge spacers and the windings to form a stiff overall beam section. The saddle supports combine the bore tube, members anchored to the bore tube, clamp rings and axial tie rods to provide three-dimensional constraint of the windings.



D9417

Figure 14 Transverse Section through the Magnet

The conceptual details of the lateral support structure and the winding arrangement are shown. The cooling passages in the windings and the flow distribution passages in the support structure are indicated, but the overall circulation pattern and flow manifolding is not shown.

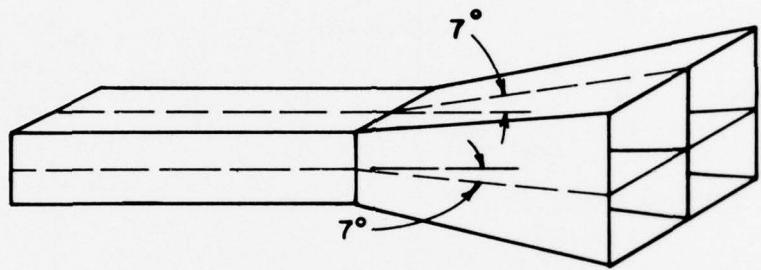


Figure 15 Multi-Cell Diffuser Configuration

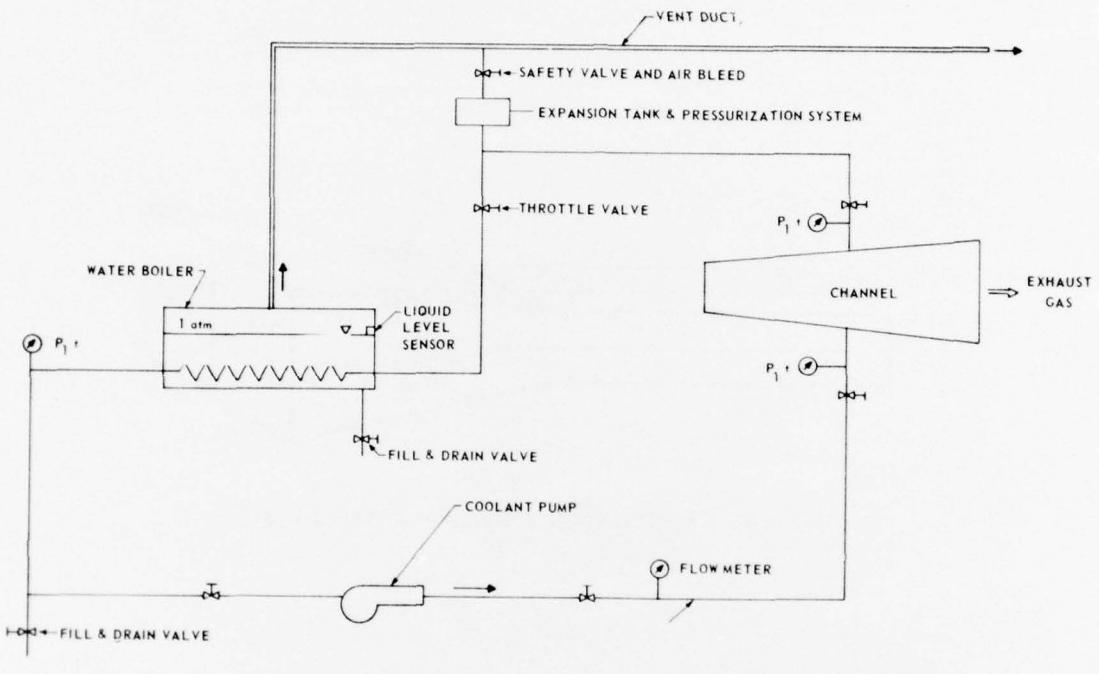


Figure 16 Flow Diagram for Channel Cooling System

a much smaller scale, have been used successfully for airborne electronics equipment cooling. Lightweight, high-performance pumps which meet anticipated temperature and pressure requirements are available and the water boiler can be custom designed on the basis of aerospace heat exchanger design experience.

C. REACTANT STORAGE AND HANDLING

A major difference between the liquid fuel system and the solid fuel system is that the liquid fuel burner requires a reactant storage and feed system, and the solid fuel burner does not, since the burner and its reactants are essentially integral. The reactant storage and feed system is an important subsystem of the liquid fuel generator and affects both the size and weight of the complete system and its operation. Differences between the two systems due to the storage, feed and handling of the reactants are discussed below.

1. Liquid Fuel Combustor

a) Operational Mode

The combustor is regeneratively cooled, using the RP fuel as the coolant. The oxidizer is liquid oxygen, fed to the combustion chamber injector by a turbo-pump which also pumps the RP through the system. The turbo-pump system was selected over a pressurized tank feed system in order to avoid pressurizing large reactant tanks. Seed is injected into the combustion chamber as a liquid from a pressurized tank. The tank is small because of the small amount of seed used.

The main operational advantage of this system over the solid propellant system is that the number of firing pulses and the minimum pulse length can be varied. The importance of this depends on the specific application. Because of the many components in the liquid fueled system, its inherent reliability is not as high as that of the solid propellant system. However, experience gained with space hardware has demonstrated that high reliability can be obtained. By using a programmable sequencing logic system in conjunction with all the start/stop and running steps, it is possible to have essentially the same one push button firing control as in the solid propellant system.

b) Storage and Feed Systems

A schematic diagram of the reactant storage and feed system is shown in Fig. 17. The system is sized for 60 seconds of operation. Briefly, the system consists of:

(i) Gas Storage Assembly - A titanium alloy helium tank with a capacity of 6 lbs at 3000 psi, fill and vent valve, isolating valves, regulators and check valves to prevent the inadvertent feedback of propellants into the gas system.

(ii) Propellant Storage Assembly - The oxygen tank is a vacuum insulated aluminum alloy tank of 3020 lb capacity with a design operating pressure of 35 psia. The fuel tank is aluminum alloy with a capacity of 1250 lbs and operating pressure of 15 psia. The cesium tank of A286 stainless steel has a capacity of 300 lbs and an operating pressure of 660 psia. The triethylaluminum used for igniting the propellants is stored at 400 psia. 21 lb of triethylaluminum is provided. The tank is made of 6061-T6 aluminum alloy.

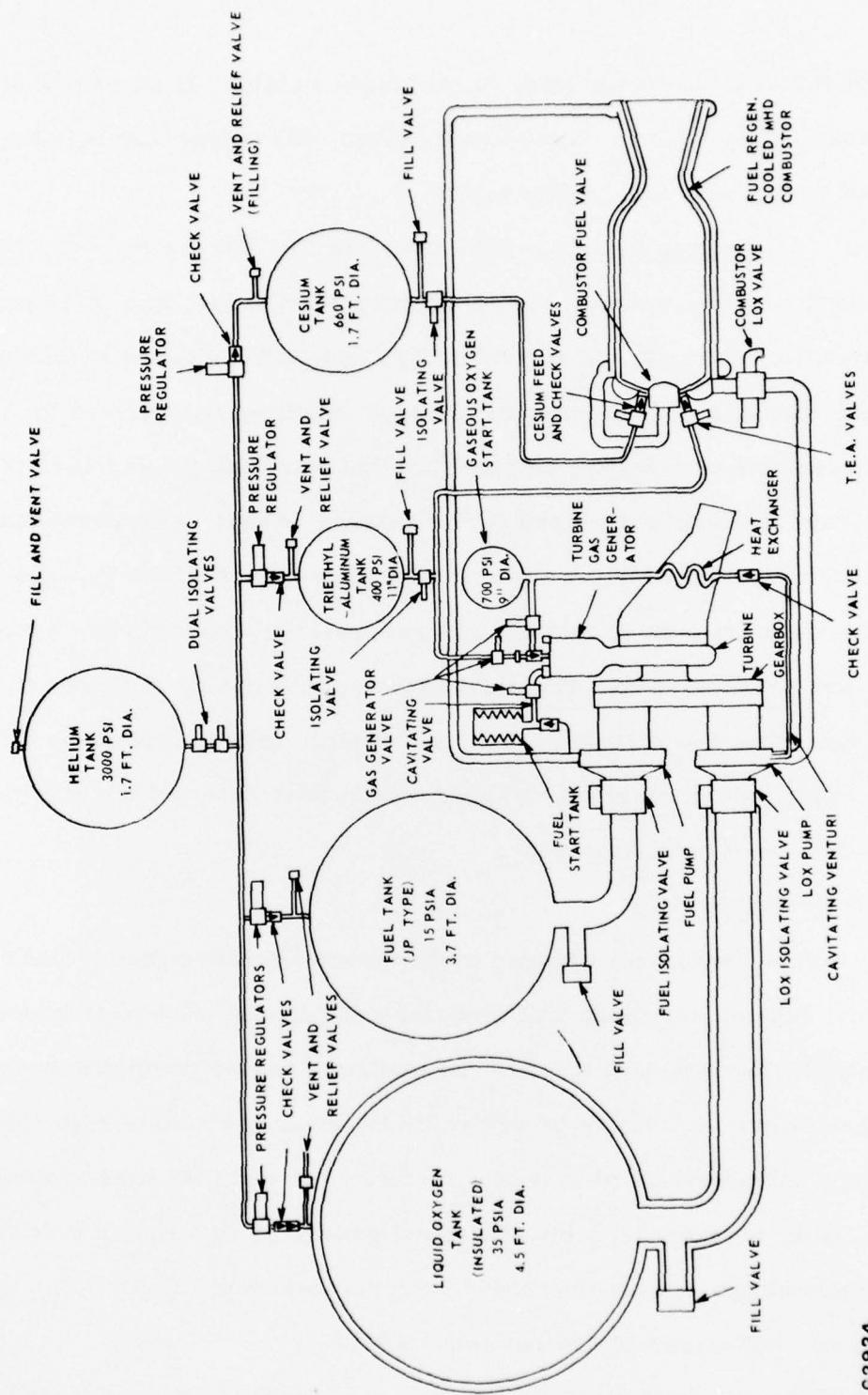


Figure 17 MHD Combustor Feed System Schematic

G2924

Spherical tanks are shown, to minimize weight. The propellant storage assemblies include manual vent valves, fill valves and isolating valves and an oxidizer tank relief valve.

(iii) Turbopump System - This consists of a hot gas turbine, gear box, oxidizer and fuel pumps, gas generator, start tanks, and turbopump control system. Pump speed control is by means of cavitating venturis in the liquid propellant feed from the pumps. Starting is achieved by using pressurized start tanks, the fuel in a bellows tank pressurized with an inert gas, and the oxidizer stored in the gaseous phase. A heat exchanger mounted in the turbine exhaust vaporizes the oxygen fed to the gas generator and the start tank so that the gas generator injector always operates with gaseous phase oxygen. The start tanks automatically recharge to full pressure when the turbopump reaches design running conditions. Check valves prevent loss of start tank charge on the inlet side and the start/stop control valves on the delivery side.

c) Ground Service

Reactant loading is required on the ground because the oxidizer is cryogenic. Ground servicing will therefore employ the elaborate procedures established for the space program. To facilitate easier servicing by not involving the aircraft, it may be desirable to mount the reactant storage system on a pallet and service it in a remote area and then load aboard the aircraft. The interface with the electrical generator is simpler than for the solid propellant system because major mechanical connections (i.e., gas generator to MHD channel) are not required.

Besides the loading requirement, a procedure is necessary for servicing the empty propellant system after landing, which is

critical when recycling the system. More and higher skilled ground personnel would be required for reloading this system versus the solid system.

d) Logistics

The shipping and storage of JP-4 and seed material present no difficulty. Shipping and storage of LOX requires more elaborate procedures, such as are used in the space program.

2. Solid Propellant Combustor

a) Operational Mode

The main operational advantage of the solid-fueled system compared to a liquid fueled system is in the simplicity of firing the gas generator. Initiation of a burn consists essentially of pushing the fire button for each required pulse, with a minimum of pre-operation checkout. Standard interlocks with the electrical power generator system would be connected to the firing circuit.

Another advantage is that the Cs seed material is cast into the grain, thus eliminating the need for a separate seed feed system.

A disadvantage of this system is the fact that the lengths of the burn and hence the lengths of the electrical pulses are fixed by the fuel grain design. The minimum pulse burn time is, normally, that required to burn an individual grain, unless emergency shut-down procedures are employed. Thus, the duration(s) of the electrical pulse or pulses are predetermined by the initial grain size and configuration. Flexibility with respect to pulse duration and interval is limited. The length of the electrical pulse from the MHD generator is essentially the same as the length of the burning pulse, because the generator produces power as long as the working gas flows through the channel. Electric power production can be interrupted

only by shutting off the magnetic field, which is not possible during the short pulse length, or by open circuiting or short-circuiting the generator, which would cause excessive electrical stresses within the channel.

b) Ground Service

The most likely mode of operation expected is that the reactant grain and the combustor/nozzle are integral, and that the complete unit will be assembled to the rest of the MHD generator for each mission. This will require careful handling of large units: for 60 second operation, the assembly is about 1.2 m in diameter, 1.6 m long, and weighs about 2000 kg. It is proportionally larger if longer operation is required. Besides the actual lifting of the combustor/nozzle/reactant unit aboard the aircraft, it is necessary to control the movement of the unit so that the gas seal between it and the generator channel can be properly accomplished.

A possible design with some handling advantages is to mount the gas generator on a structural pallet which would take up the thrust load, support the combustor, and act as the lift structure for putting the unit aboard the aircraft. This in turn would be attached to the airframe when in place.

Another mode of operation is to load the reactant grain into a combustor shell which remains attached to the MHD channel. In this case, the nozzle would require cooling so that it need not be replaced after each mission as would be necessary for the ablatively cooled nozzle used in the first mode of operation described above.

c) Logistics

The logistics plan for the gas generator would be the same as that used for missile weapon systems. One added feature which can be considered is the recycling of the empty propellant case to the propellant

loading contractor. The shipping containers presently used for missiles are returned to the factory, and the empty combustor cases can be sent with them. Rocket motor cases can be recycled and considering the end use application, such an approach is justifiable and cost effective.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

A study was performed of MHD generators operating at power densities in the channel of 500 MW/m^3 and 1000 MW/m^3 . Operation at 500 MW/m^3 can be achieved either by use of hydrocarbon fuel (RP-1 or JP-4) and oxygen, with cesium seed, or by use of a cesium-seeded double-base solid fuel. Major characteristics of these systems are summarized below, for generators producing 30 - 35 MW (nominal) power output.

	RP/O ₂ System	Solid Fuel System
Power Output [MW]	31.5	33.2
System Dry Weight [kg]	2305	1695
Mass Flow Rate [kg/sec]	30	30
Total Weight (60 sec operation)[kg] (includes reactants and coolant)	4625	3280
Peak Magnetic Field [T]	4.6	3.6
Overall Diameter [m]	1.6	1.3
Overall Length [m]	3.7	3.7

The major technical risk arises from the high potential for damage which exists in the channel.

Major development is judged to be required for the following components:

1. Lightweight superconducting magnet.
2. Burners for pulsed operation, if required.
3. Lightweight MHD channel.

The magnet is regarded as a critical component because a) failure to produce the required fields would result in degradation of generator power output; b) the magnet is the heaviest single component of the system, and represents about 50% of the system dry weight (more if shielded); c) the gap between existing technology and required technology is large, with respect to size and weight of the required magnets compared to magnets which have actually been built.

The burner is another important component because of its dominant influence on the gas electrical conductivity, through the effects of burner losses on gas temperature. Relatively small reductions in gas temperature, due to increases in burner losses, result in large reductions in electrical conductivity, and hence, in generator power output. Development of burners for continuous operation represents a relatively straightforward application of existing rocket technology, either solid or liquid fueled. Some modifications are necessary to ensure seed vaporization and uniform seed distribution in the gas. This is probably more easily accomplished with solid fuel burners than with liquid fuel burners. For pulsed operation, with the reactants to be used for the MHD generator, some development of burners will probably be necessary, particularly of solid-fueled burners, as this type of operation represents a larger departure from existing rocket engine technology than does continuous operation.

The channel operates in a regime in which the potential for damage resulting from axial electrical breakdown is much higher than in other MHD channels operated to date. Therefore the channel must be considered a high-risk component. Development of lightweight power-producing channels is

required. Lightweight model channels have been built and operated under hot gas flow conditions, but not yet to produce power.

Operation at 1000 MW/m^3 increases the risks for the magnet, because of the higher fields required, and for the channel, because of the more severe electrical stresses, particularly the axial electric field. System weights are reduced by about 10%, compared to operation at 500 MW/m^3 . Risks can be reduced by use of reactants producing higher electrical conductivity, which allows lower magnetic and electric fields. However, the disadvantage, perhaps crucial, of such reactants is that they are highly toxic and difficult to handle.

A development plan and suggested schedule is shown in Fig. 18 for generator operation at 500 MW/m^3 . The plan is in three phases, as follows:

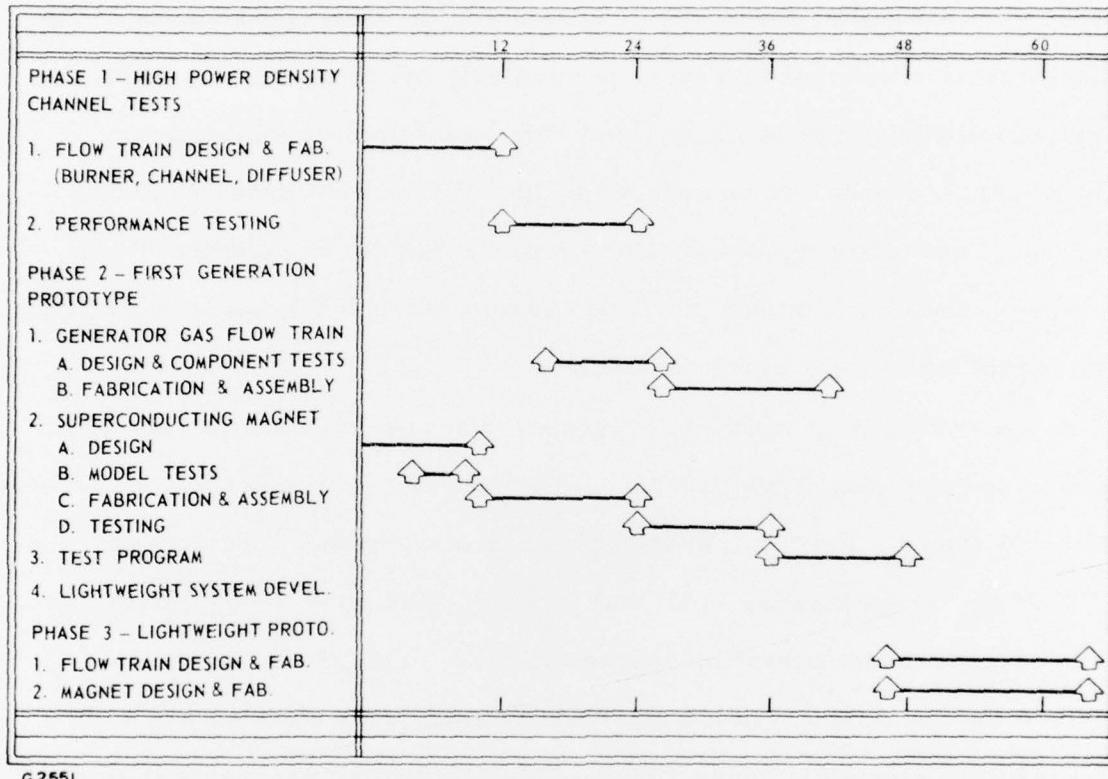
Phase 1 - Fabrication and operation of a channel operating at 500 MW/m^3 in an existing MHD test facility. The objective of this phase is to verify channel operating characteristics. This phase would also include the development of a burner which produces a working gas with the required electrical conductivity. The flow train components in this phase need not be light in weight, and the magnet need not be superconducting.

Phase 2 - Design, construction and testing of a first generation prototype generator. This generator would use a superconducting magnet and would be light in weight, although not as light as the eventual airborne units.

Phase 3 - Fabrication of a flightweight generator.

The three phases of the development plan would overlap to some extent, as shown in Fig. 18, as experience was gained during each phase which would enable the next phase to be started. The first phase would be completed in twenty-four (24) months, the first-generation ground based

DEVELOPMENT PLAN FOR HIGH POWER DENSITY (500 MW/m^3) MHD GENERATORS
NET POWER: 30 - 35 MW



G2551

Figure 18 Development Plan for High Power Density (500 MW/m^3) MHD Generators. Net Power: 30 - 35 MW

prototype (Phase 2) would be completed by fifty-four (54) months and the flightweight generator (Phase 3) by sixty-eight (68) months. The program could be advanced by eighteen (18) months by eliminating Phase I, and by eliminating the test program for the superconducting magnet. With this program modification, the first generation prototype would be completed in thirty-six (36) months and the flightweight prototype in fifty (50) months. The technical risk of the shortened program would be considerably higher.

Operation at 1000 MW/m^3 would add an estimated eighteen (18) months to the program, to solve problems which would be expected to occur in the more highly stressed channels and higher field magnets which would be required.

REFERENCES

1. Louis, J.F., Lothrop, J., and Brogan, T.R., "Studies of Fluid Mechanics using a Large, Combustion-Driven MHD Generator", Avco Everett Research Laboratory Research Report 145 (March 1963).
2. Teno, J., Brogan, T.R., et al., "Research Studies and the Development of MHD Generators and Accelerators", Final Report, Contract AF40(600)-1043 prepared by Avco Everett Research Laboratory, Everett, Massachusetts (September 1969).
3. Teno, J., Brogan, T.R., DiNanno, L.R., "Hall Configuration MHD Generator Studies", International Symposium on MHD Electric Power Generation, Salzburg, Austria (July 1966).
4. Teno, J., Liu, C., and Brogan, T.R., "Boundary Layers in MHD Generators", 10th Symposium on the Engineering Aspects of MHD, M.I.T. (March 1969).
5. Kessler, R., "MHD Power Generation (VIKING Series) with Hydrocarbon Fuels", Technical Report AFAPL-TR-75-97 (September 1975).
6. Bangerter, C., Hercules Powder Company, Private Communication (1976).
7. Kessler, R., Sonju, O.K., et al., "MHD Power Generation (VIKING Series) with Hydrocarbon Fuels", Technical Report AFAPL-TR-74-47, Part III (November 1974).
8. Lockheed Propulsion Company, "Study, Design, Analysis, Fabrication and Test of a Solid Propellant Pulse Rocket Motor", Technical Report AFAPL-TR-65-122, (1965).